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Application of a Geographic Information System to Rainfall-Runoff Modeling

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The planning of water resource projects relies heavily on geographic information describing river basins. Information about topography, land use, vegetative cover, soil type and erodibility are needed in rainfall-runoff modeling, flood damage determination, soil erosion studies, and water quality studies. Geographic Information Systems (GIS) have been developed to take advantage of the data handling capability of digital computers for storage and use of geographic information. With a GIS, less averaging is required and greater use of readily available physical data is accomplished. The computer program system, HEC1-ADAPT, combines two existing models. ADAPT is a GIS that was originally developed by W.E. Gates and Associates to aid in sewer design. HEC-1 is a rainfall-runoff model that was developed at the Hydrologic Engineering Center of the Corps of Engineers. These two modeling systems are linked together to provide a GIS-based watershed-runoff capability. This report describes the testing of the HECI-ADAPT system for rainfall-runoff modeling.

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Master of Science Thesis
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Preface

This work was performed by Mr. David L. Thirkill while attending the University of California at Davis. The Hydrologic Engineering Center (HEC) contracted with the University for this research and this report was Mr. Thirkill's M.S. Thesis. Mr. Arlen Feldman of the HEC was on Mr. Thirkill's thesis committee.

The ADAPT software used in this research is no longer available. It was proprietary software of W.E. Gates and Associates. The Corps has not continued with its usage because of the many new commercial systems now available.

The modelling concepts discussed herein with the ADAPT software could be duplicated with currently available vector-based geographic information systems (GIS) e.g. ARC/INFO TIN model. HEC is continuing research in the area of GIS-based hydrologic analysis.

January 1991

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AKNOWLEGEMENTS

The author would like to express his appreciation to the people at the HEC many of whom provided assistance and were available to discuss problems throughout the course of this testing program. The author is particularly indebted to Mr. Arlen Feldman, who served as a committee member, and to Mr. Darryl Davis, who also reviewed and assisted in editing this paper.

The author expresses special gratitude to Dr. Johannes DeVries who served as committee chairman and provided much guidance, funding and humorous asides during the authors graduate program.

The author is also indebted to Dr. Robert Burgy who served as committee chairman during the latter period of the authors graduate program.

GLOSSARY OF ABBREVIATIONS

ABBREVIATION	DESCRIPTION
ADAPT	Areal Design And Planning Tool, geographic information system of the HEC1-ADAPT system
CN	Curve Number
DTM	Digital Terrain Model
GIS	Geographic Information System
HEC-1	Rainfall-runoff model developed at the Hydrologic Engineering Center
HECAD	Interface program connecting ADAPT and HEC-1
SAP	Single Attribute Polygon
SCS	U.S. Soil Conservation Service
TIN	Triangular Irregular Network
UAP	Unique Attribute Polygon
USGS	U.S. Geological Survey

1. INTRODUCTION

1.1 Watershed Modeling Using Geographic Information Systems

The planning of water resources projects relies heavily on geographic information describing river basins. Information about topography, land use, vegetative cover, soil type and erodibility are needed in rainfall-runoff modeling, flood damage determination, soil erosion studies and water quality studies. It is often necessary to work manually with this data to derive input for various simulation models and resource studies. Geographic Information Systems (GIS's) have been developed to take advantage of the data handling capability of digital computers enabling more detailed modeling and easing the burden of much of this hand work.

A basic problem confronting water engineers has been how to handle the heterogeneity in the geographic characteristics within a basin. Because of their efficiency in handling data, GIS's have been applied to this problem. A GIS allows engineers to model the hydrologic diversity within a watershed with a resolution dependent only on the size of the elements chosen. It is generally felt that modeling smaller, more homogeneous areas yields a more accurate simulation (1,6,20,22,23,25). With a GIS, less averaging is required and greater use of readily available physical data is accomplished. Derivation of routing and runoff coefficients is therefore based on a more accurate physical model.

A GIS can also provide the basis for modeling the hydrology

of ungaged river basins and for studying the hydrologic impact of physical changes (such as urbanization) within a river basin.

The computer program system, HEC1-ADAPT, combines two existing models. ADAPT is a GIS that was originally developed by W.E. Gates and Associates to aid in sewer design (34). HEC-1 is a rainfall-runoff model that was developed at the Hydrologic Engineering Center of the Corps of Engineers (18). These two modeling systems are linked through an interface program called HECAD, also developed (under contract to the HEC) by W.E. Gates and Associates (34). This report describes the testing of the HEC1-ADAPT system for rainfall-runoff modeling.

1.2 Objectives of This Study

A major objective of this study is to test the ability of the HEC1-ADAPT system to model rainfall-runoff processes on ungaged basins. Thus, the initial model of each of the two basins studied is developed without using streamgage data. A second objective is to determine the effect of model resolution on the outflow hydrograph. Castro Valley, the smaller test basin, is therefore modeled using two different resolutions. The larger test basin, Potter Valley, is modeled using a single resolution. A third objective is to test the flexibility of the model. To evaluate this, a small urban basin and a large non-urban basin are used in the testing program.

Before starting the testing program, it was necessary to accomplish three tasks. The first task was to make sure all necessary programs and hardware were available to develop a

complete GIS. The second task was to check each program to make sure it worked properly. And the third task was to check computational routines to be sure reasonable numbers were being generated. This work is described in Appendix A of this report.

2. BACKGROUND

2.1 Types of GIS's

Geographic Information Systems (GIS's) are data base systems that are used primarily for managing spatial geographic data. In general, GIS's have the following characteristics: some method for entering and editing data for the data base, various systems for displaying information stored in the data base and a capability to perform calculations and sorting on data in the data base (23). The types of geographic information stored in GIS's are dependent on the purposes for which the GIS's are developed.

There are two basic types of GIS's: the polygon system and the grid-cell system. The polygon system employs an irregular polygon areal unit for spatial representation. This system attempts to represent exact boundaries of areas, points and lines. Polygon GIS's are used to store maps in computers and to prepare other maps at different scales or projections (23). Although the systems can have high geographic fidelity, they have very limited analytic capability .

The grid-cell system is an alternative system with much improved analytic capability (9,23). With the grid-cell system, the area of interest is broken up into square or rectangular elements with various data types and values associated with each element or cell. Analysis is usually done cell by cell. Searching, calculation of distance, production of overlay maps, and suitability analysis are typical studies carried out using

this methodology (9,23). Ease of manipulation and storage of data using the grid cell representation has resulted in widespread use of the format as a foundation in many GIS's (9). A major problem associated with grid-cell systems, however, is that of resolution (7,23,15). In order to capture detail, a large number of grid-cells are required, increasing both the computer storage requirements and computing costs. Even with a small grid size, the system is unable to precisely represent point locations, lines, or spatial boundaries using the nodes of the rectangular grids.

A combination system, the polygon-to-grid system, attempts to take advantage of the good qualities of both the above systems. Data is first represented using polygons and then translated by computer to a grid system for analysis purposes (23).

2.2 Digital Terrain Models

Digital Terrain Models (DTM's) are considered to be a special type of GIS (23). In addition to the usual attribute data contained within the GIS, DTM's also contain information on terrain elevation.

DTM's are normally produced using either the rectangular grid or the triangular irregular network, a special type of polygon representation (7). The vertices of the triangles (nodes) contain coordinate-elevation data and the areas within the lines connecting the nodes contain spatial data. The disadvantage of rectangular grids for terrain modeling is that the projection of

the grid pattern onto a complex surface is warped. The difficulty of using the system lies in the attempt to derive slopes and areas from the warped quadrilaterals. Use of the triangular irregular network (TIN) avoids this problem since the vertical projection still yields a triangular plane that best fits the complex surface (7). Surface slopes and areas can be computed easily. Another advantage of the TIN is the ability to vary the triangle size. Thus, areas of complex topography can be accurately modeled by using more triangles. Because of this variable resolution, the TIN is inherently more efficient than the grid system for modeling terrain. The DTM being investigated in this report is contained within ADAPT (34) and is described below.

2.3 ADAPT

ADAPT uses a TIN system to store data. Terrain is represented as a faceted surface with each facet a triangular plane. Increased accuracy of representation (resolution) is obtained where necessary by increasing the number of triangles. This "variable" resolution increases the computational efficiency of the method.

Triangle sides and vertices are chosen to represent important terrain features such as ridges, peaks, slope breaks, passes and streams, as well as the natural boundaries between different soil and land-use types and the artificial boundaries delineating political districts. Like the grid system, each triangular element in the network is treated as a homogenous cell. Each cell contains information such as land use, soil

type, political jurisdiction as well as slope, slope direction, area and elevation. ADAPT includes routines which use the topology of the DTM to determine stream and overland flow networks. The ADAPT system incorporates the good boundary representation of the polygon system while retaining the analytical capability of the grid-cell.

2.4 Digital Terrain Model Construction Using ADAPT

The first step in producing the DTM is to delineate the study area boundary on topographic maps. Normally, 7.5 minute USGS quads are used. Next, the process of triangulating the basin is begun by overlaying a sheet of mylar on the quad. Triangles representing the major topographic features are drawn on this overlay. Each triangle should represent a uniform or nearly uniform planar section of the topographic map. The triangulation is digitized by recording the coordinates and elevation of each triangle vertex using a digitizer connected to a computer. A file containing coordinate and elevation data for each triangle vertex is created this way.

This file is used to build two additional files: a triangle file and a vertex file. The ADAPT program used to accomplish this identifies triangles with common vertices and assigns unique vertex and triangle numbers. It then uses this information to determine triangle adjacencies and to identify basin boundaries. The resulting triangle file consists of vertex and adjacency information along with coordinate, elevation, slope and slope angle data. Each vertex in the vertex file contains a list of

triangles which share it as a common vertex in addition to coordinate and elevation data. The end result of this process is a DTM. Soil and land use data need to be incorporated to complete the GIS.

The additional data required to produce the GIS are typically derived from soil and land use maps commonly available from the U.S. Soil Conservation Service (SCS) and other agencies involved in resource planning. This information may be incorporated into the triangle file by either digitizing or by manual techniques. Triangles that share the same attribute characteristics with neighbors (e.g. same land use or soils) are aggregated into polygons. The ADAPT term for these polygons is "unique attribute polygon" (UAP).

If a digitizing procedure is used, the boundaries of each polygon are digitized and an ADAPT program assigns land use and soils values to individual triangles by determining what triangles are internal to the polygon boundary. If done manually, the information is entered on a triangle-by-triangle basis.

Further processing by the ADAPT system produces a network file containing stream and overland network data. This file contains those triangle sides which the program has defined as stream segments (links). The ADAPT system automatically assigns stream-link status to a triangle side if it is a common side between two triangles that drain toward each other. Any other triangle side can be manually assigned this status.

Coordinate data, upstream and downstream vertex numbers and

elevation data for each link vertex are part of the file. The file also contains channel roughness values and optional information describing stream cross-sections (for normal depth routing), and an overland network of contributing triangles for each stream link.

2.5 HECAD

HECAD is the interface program designed to generate input data (on disk) for HEC-1 (34) using information stored within the ADAPT data base and auxiliary files. The auxiliary files include: a soil matrix file containing information on each soil type; a drainage network file containing stream and overland networks and channel information required for routing; an auxiliary file containing information describing each channel link for the normal-depth routing option; a sub-watershed identifier contained in the drainage network file; a rain gage file containing the raingage number, type and location; a reservoir file containing routing characteristics; a diversion file describing location and amount of diversion; and a calibration file.

The calibration file contains numerical values of infiltration, roughness and percent imperviousness as a function of land use and soil hydrologic group. HECAD derives areally-weighted averages of these parameters for each sub-basin using the calibration data in the calibration file and the soil and land use data in the data base and auxiliary files. The following sections describing HECAD are paraphrased from the W.E.

Gates documentation for HEC1-ADAPT (34).

2.5.1 Sub-basin Definition

HEC-1 is set up to run using the sub-basin as its elementary areal unit. At present, HEC-1 does not support overland routing between sub-basins. Therefore, triangle-to-triangle routing cannot be accomplished using HEC-1. Some amount of aggregation must therefore take place. In HEC1-ADAPT, this is accomplished by defining each stream link and the triangles that drain to it as the equivalent HEC1-ADAPT sub-basin.

The triangles that make up each sub-basin are identified through a computer analysis of the terrain and topologic information stored within the data base. Since each ADAPT sub-basin is typically composed of more than one triangle, a certain amount of lumping (averaging) must occur to derive the parameters which characterize the sub-basin. The degree of lumping is a function of triangle size.

ADAPT also has the capability of defining sub-watersheds. Sub-watersheds are portions of the overall data base and are identified using stream links. The sub-watershed definition is a windowing capability which makes it possible to model specific portions of the data base without having to use the entire data base.

2.5.2 Overland Flow Parameters

Overland flow is controlled by the quantity and temporal pattern of rainfall, by infiltration and evaporative losses, and by the process by which water travels to the stream channel.

In HECAD, the gage locations used in calculating rainfall

are stored in the raingage file. Total rainfall is computed for each sub-basin using a weighting function in which the weight is inversely proportional to the distance from the gage to the centroid of the sub-basin. The user can limit the number of gages used for each sub-basin by specifying a maximum distance or a maximum number of gages. Up to five gages may be used to define storm totals. The gage closest to a sub-basin is used to define the temporal distribution.

Two methods are available for modeling losses in the HEC1-ADAPT system: initial and uniform loss rate and SCS curve number (CN) (29). Numerical values of initial and uniform loss rate and CN are stored within the calibration file as a function of both land use and soil hydrologic group. The mix of land use and hydrologic soil group within each triangle is stored in the data base. HECAD first calculates loss rate parameters on a triangle-by-triangle basis and then computes an areally-weighted average for each sub-basin by accessing the information stored in both the calibration file and the data base.

The interface also includes an option for adjusting CN based on antecedent precipitation and season.

Both methods of calculating losses apply only to pervious areas. The impervious area of each triangle is calculated by HECAD using calibration file data relating land use to percent imperviousness and land use data from the data base.

Four methods are available in HEC1-ADAPT for transforming rainfall excess into sub-basin runoff hydrographs: Clark Unit

Graph, Snyder Unit Graph, SCS Dimensionless Graph and Kinematic Wave. For the Clark Unit Graph method, HECAD computes a time-area curve and the two parameters: time of concentration and storage coefficient. Manning's equation is used to derive velocity from which travel time is computed. The roughness coefficient is derived for each triangle based on the land use as stored in the data base and the roughness supplied by the calibration file. Slope data are derived from the data base. The travel time and area associated with each triangular element are used to develop a time-area curve for each sub-basin. Time of concentration and storage coefficient are computed respectively as the longest triangle travel time for the sub-basin and as the areally-weighted travel time for the sub-basin. The storage coefficient can also be computed by specifying a ratio R/(Tc+R), where R is storage coefficient and Tc is time of concentration for use with all sub-basins.

Similar procedures are used to derive the Snyder and SCS parameters. For the Snyder Method, lag is computed as area-weighted travel time, the peaking coefficient is supplied as input by the user and the time-area curve is developed in the same way as for the Clark. For the SCS method, lag is also calculated as the area-weighted travel time.

The Kinematic Wave Method parameters are slope, roughness and overland flow length. Area-weighted values of slope and roughness are derived using the slope and roughness data from the data base and roughness data stored as a function of land use in the calibration file. The overland flow length is calculated by

one method if two overland flow planes converge to a central channel and by a different method when a single overland flow plane drains to the channel.

2.5.3 Stream Parameters

The three stream routing methods included in HEC1-ADAPT are: Kinematic Wave, Muskingum and normal-depth. All Kinematic Wave parameters (channel length, slope, roughness shape, width and side slopes) are calculated or extracted from the drainage network file and auxiliary network file. Muskingum K is assumed to be equal to the reach travel time as computed using Manning's equation. The number of routing steps is computed as travel time divided by the time step parameter supplied as input by the user. Muskingum X is also supplied by the user and is the same for all channels. For normal depth routing, cross-section data and Manning's roughness are stored in the auxiliary network file. Reach length, slope and the datum elevation are derived from the data base.

Reservoir routing, base flow and channel loss parameters may also be input. Reservoir routing is accomplished by passing flow through links identified as reservoirs with no transformation. Storage routing is performed only when the downstream end of a reservoir link is encountered. Parameters required for reservoir routing are stored in the reservoir file.

Base flow parameters entered by the user are: base flow yield in cfs/square mile, a base flow ratio by which the peak flow is multiplied to determine when the recession part of the hydrograph starts and a recession coefficient describing the

slope of the recession curve. A constant channel loss rate (in cfs) and a parameter representing the percentage of remaining flow after constant loss is subtracted out may also be entered by the user.

2.5.4 Plotting Capability

The graphics capability of ADAPT is one of the systems most useful aspects. A series of plots used to develop the Castro Valley model are shown to demonstrate this capability.

Figure 1 shows a TIN for the Castro Valley. This plot is used to check for errors in the vertex and triangle files. Contour and slope direction plots, Figures 2 and 3, are also used for error checking. The contour plot can be overlayed on the original topographic map to spot-check elevations. The slope direction plot is useful for insuring that all triangles drain inward along the watershed boundaries. If the topography is not modeled satisfactorily, the triangle network may require modification. Figures 4 and 5 show land use and soil polygons while Figure 6 shows the unique attribute polygons. The last plot of this group, Figure 7, shows a drainage network plot superimposed on the contour plot and demonstrates the overlay capability of the system. Because of the high quality of these plots, any of them can be used as figures or displays in reports.

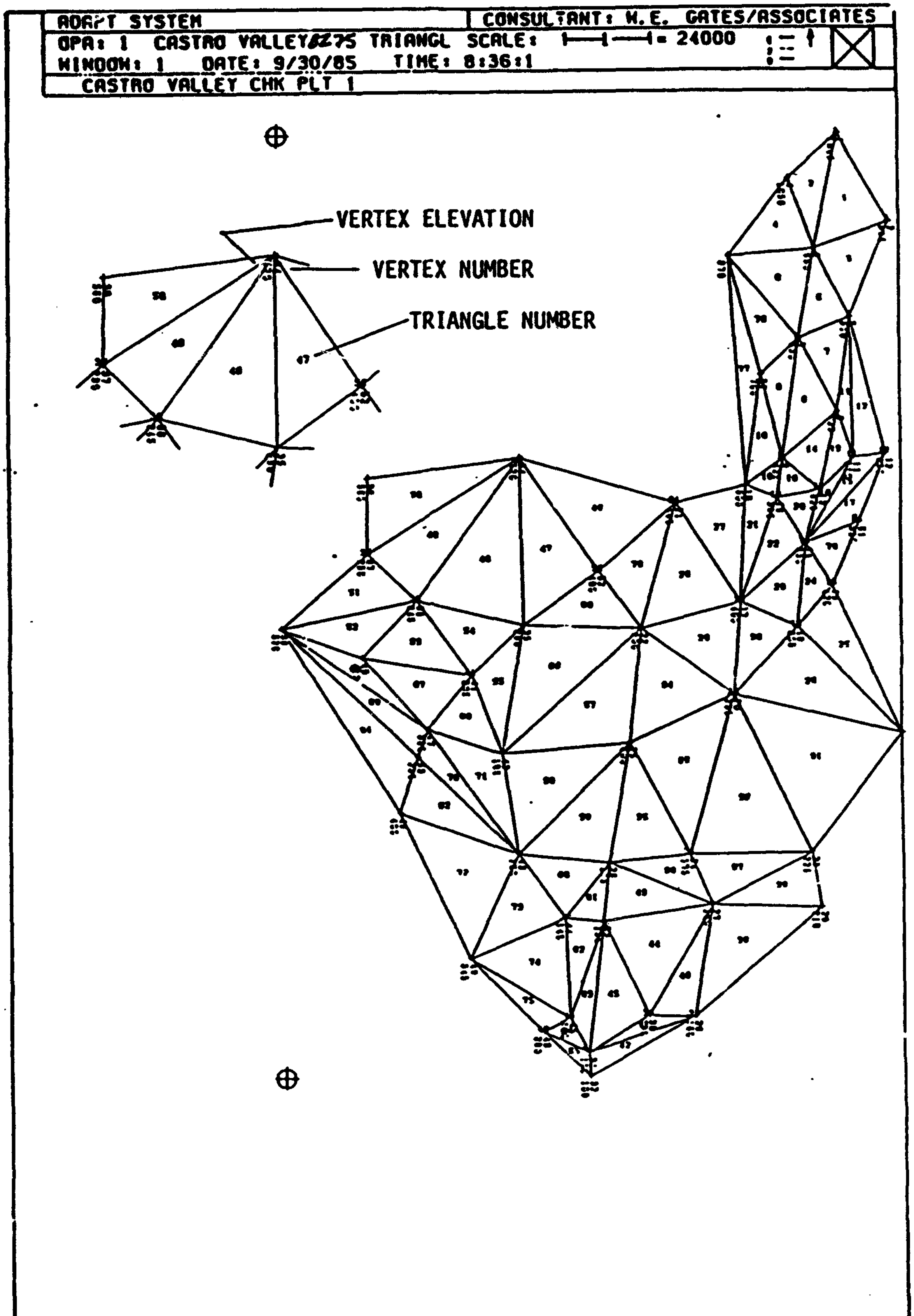


FIGURE 1 CASTRO VALLEY TIN

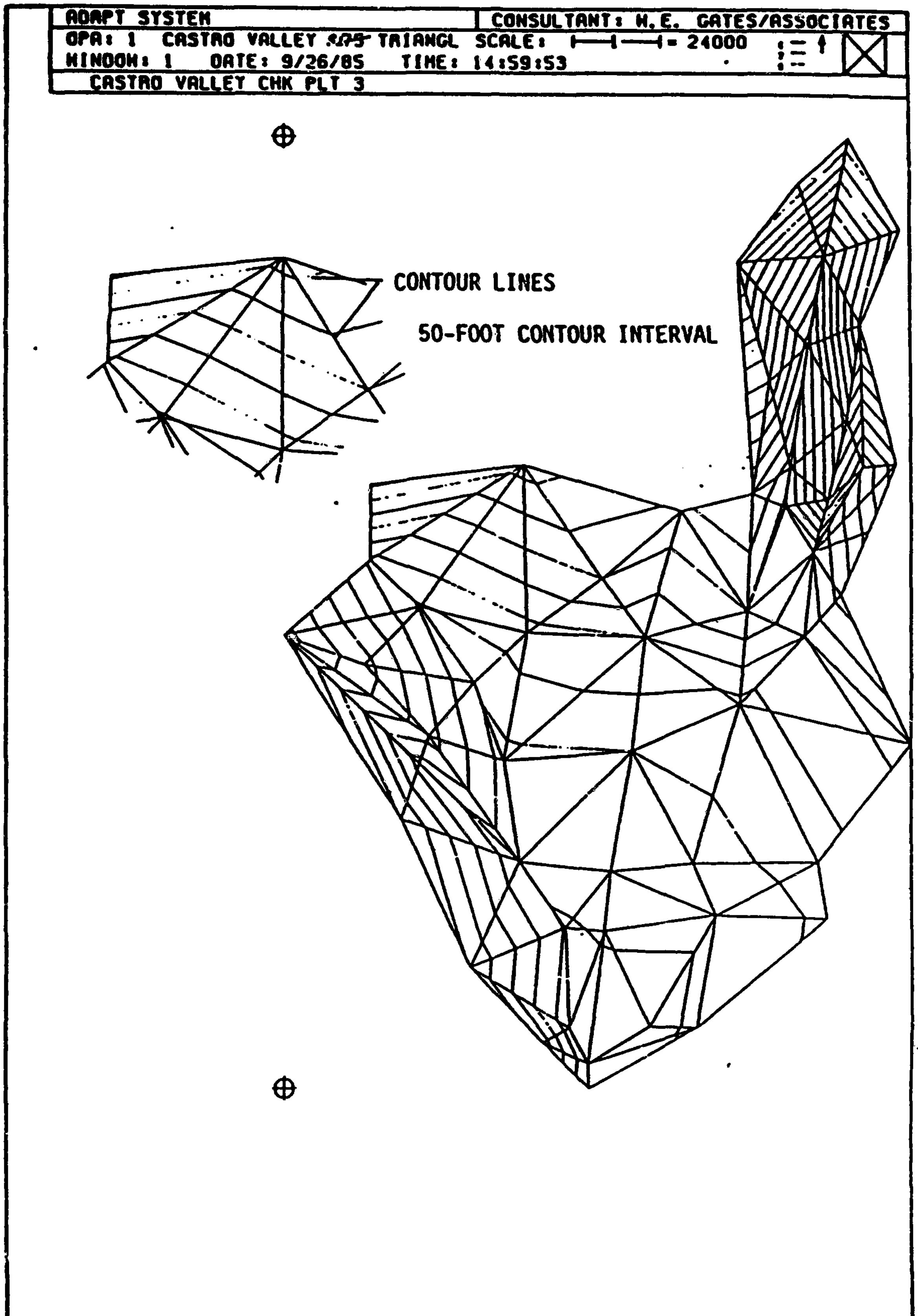


FIGURE 2 CASTRO VALLEY CONTOUR PLOT

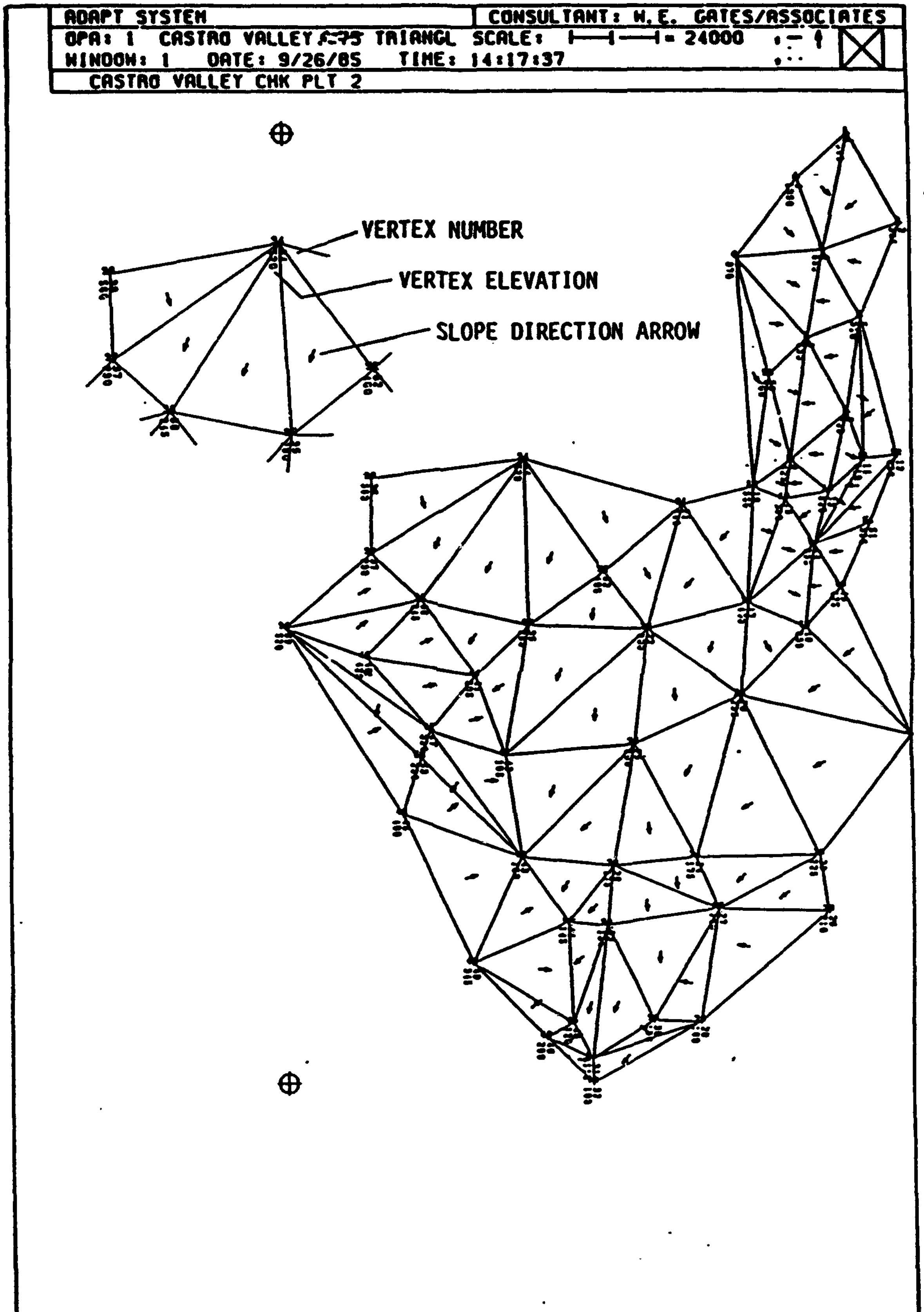
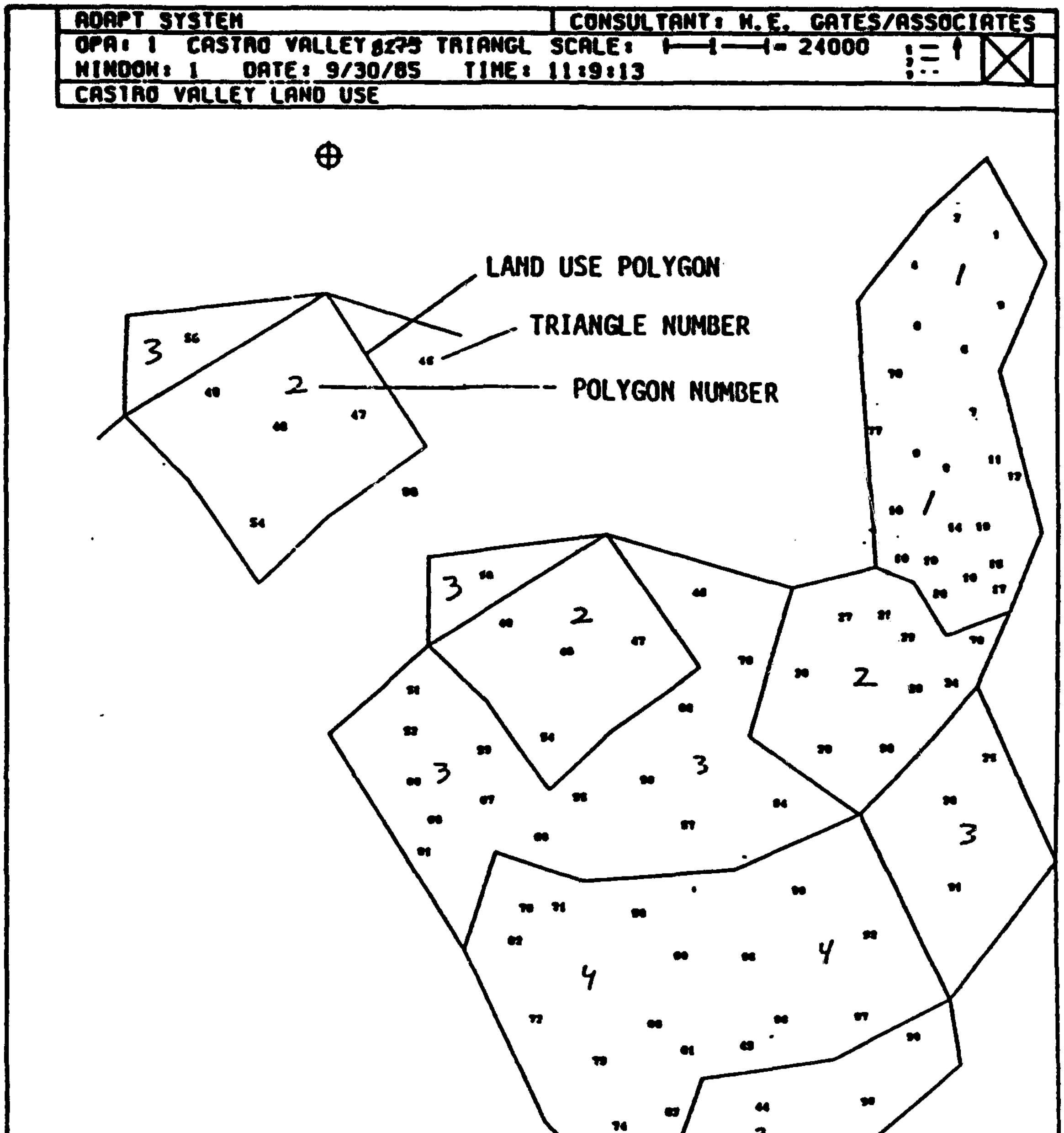


FIGURE 3 CASTRO VALLEY SLOPE DIRECTION PLOT



NUMBER	LAND USE
1	NATURAL VEGETATION
2	LOW DENSITY HOUSING
3	MEDIUM DENSITY HOUSING
4	HIGH DENSITY HOUSING/COMMERCIAL

FIGURE 4 CASTRO VALLEY LAND USE POLYGONS

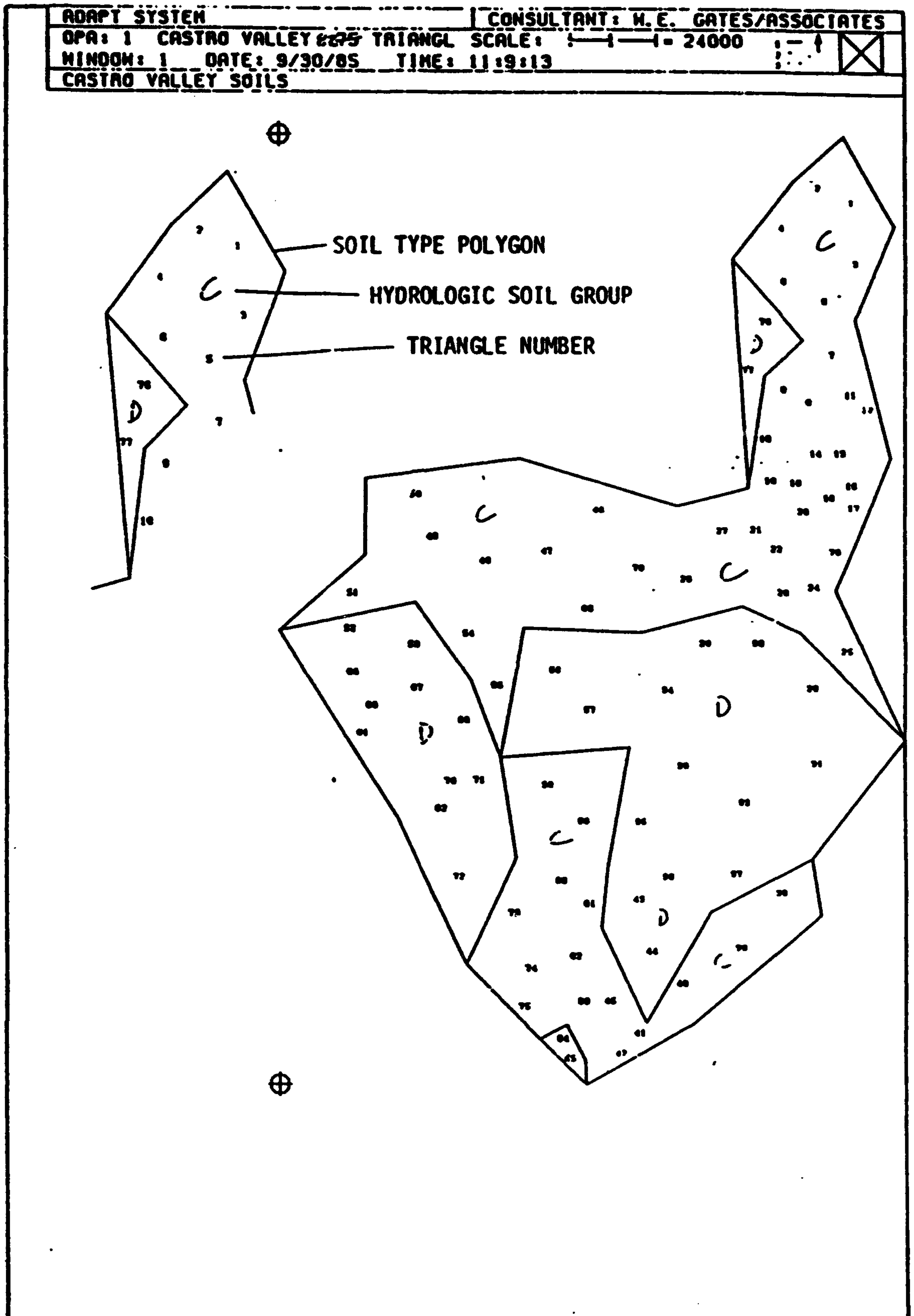


FIGURE 5 CASTRO VALLEY SOIL TYPE POLYGONS

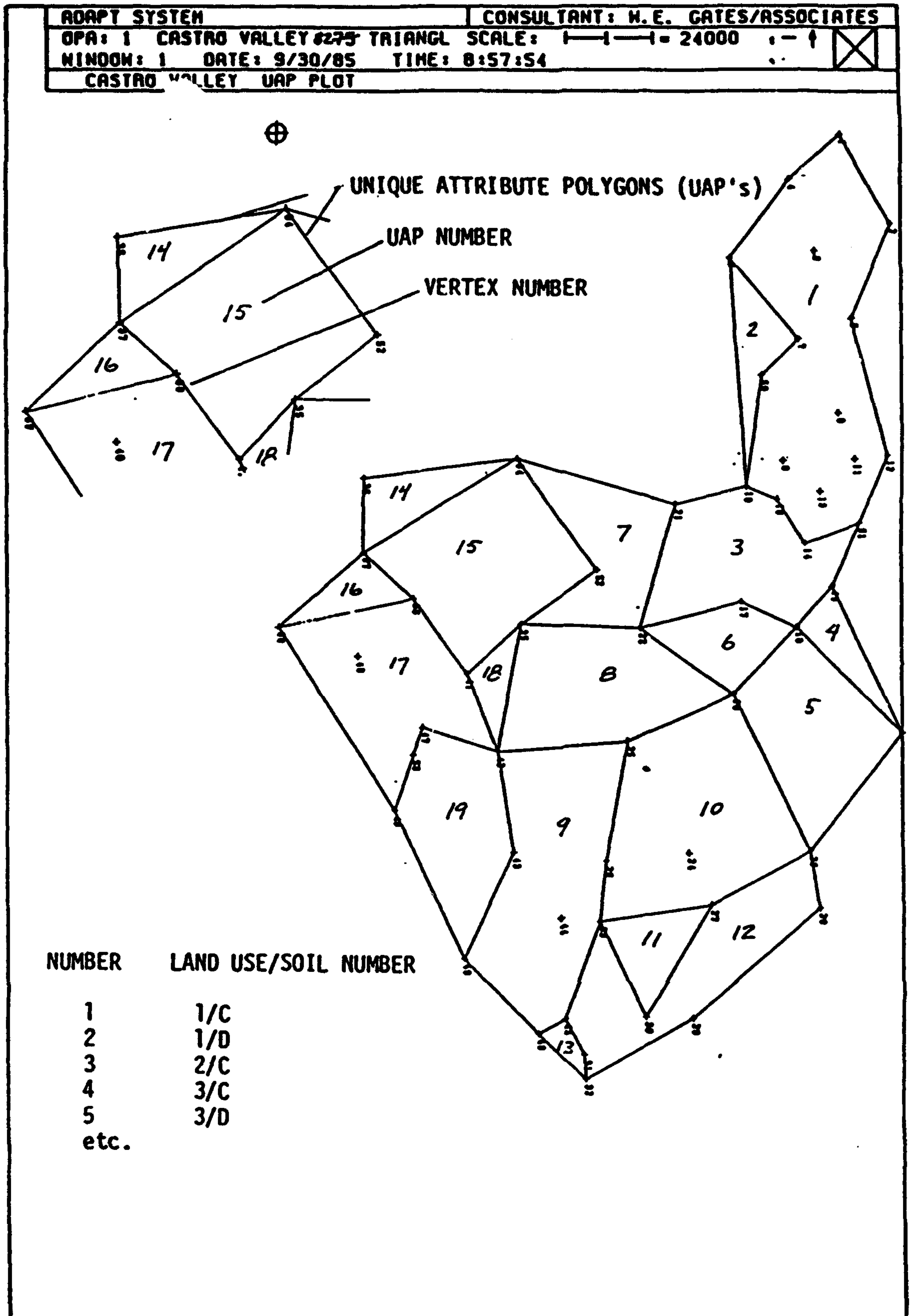


FIGURE 6 CASTRO VALLEY UNIQUE ATTRIBUTE POLYGONS

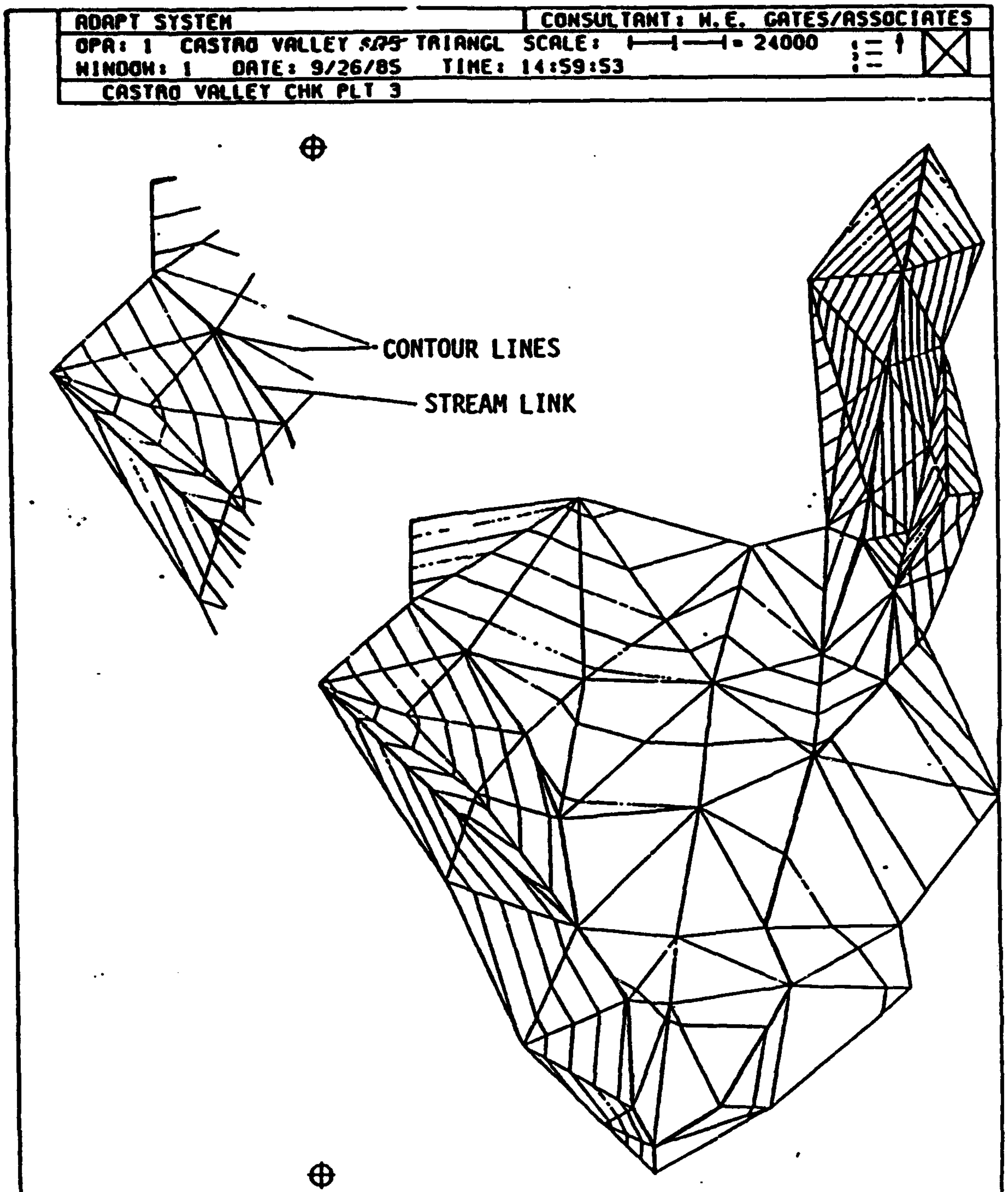


FIGURE 7 CASTRO VALLEY CONTOUR AND DRAINAGE NETWORK PLOT

3. LITERATURE REVIEW

This literature review discusses papers on a wide range of water resource applications for which GIS's have been developed. Papers are listed in chronological order for ease of presentation and to provide a sense of the technological evolution this method has experienced. Some of the early grid-based systems were used strictly as organizational aids. The new TIN-based systems are being employed in increasingly sophisticated models which take great advantage of their many capabilites.

Pentland and Cuthbert, 1971 (28). This paper describes a square grid method used to automate the determination of regional hydrologic relationships. The grid method provides an efficient means of integrating hydrometric, meteorologic and physiographic data. Regression analysis is used to define mean annual precipitation, temperature and runoff in each grid. These results and physiographic grid data are used in a second regression analysis to define monthly flows at ungaged sites. A stochastic model is then applied to generate synthetic flows for operational hydrology.

Huggins, Burney, Kunder and Monk, 1973 (22). The watershed model described in this paper is based on subdividing catchments into grids which are assumed uniform with respect to hydrologic variables. Response of each grid is characterized by deterministic equations. Interaction between individual grid elements and composite watershed response is analyzed by integrating the continuity of mass equation over the whole basin.

Seader, 1974 (32). A model called "DYLAM II" is used to project land use patterns for the purpose of predicting surface runoff. Alternative future scenarios are investigated to derive a range of future conditions. A grid method is used to input and output data.

Grayman, Males, Gates and Hadder, 1975 (11). This paper describes ADAPT and an application of ADAPT to water quality modeling.

Charbonneau, Fortin and Morin, 1975 (1). The Cequeau Model uses a grid system to define surface elements. The model assigns each cell a maximum and minimum temperature and precipitation value based on computations using data from existing meteorological stations. A hydrologic balance is done with "more or less" sophisticated math models which describe individual hydrologic processes. This is the "production" part of the model. A "transfer" part models the movement of water from cell to cell using a "transfer coefficient" which is a function of the physiographic characteristics of each grid.

HEC, 1975 (14). This report describes and illustrates the application of data management and analytical techniques developed by the HEC for application in comprehensive flood plain information studies. The technique uses gridded geographic data to analize the effects of alternate land use patterns on flood hazard, general damage potential and environmental status of the study area. AUTOMAP II, a program developed by the Environmental Systems Research Institute in Redlands, California, is used to

manipulate the data and is a key to the techniques developed.

Fabos and Joyner, 1976 (10). The model in this paper provides a procedure to assess special resources hazards and development-suitability potentials to aid in planning. A mapping system called "COMLUP" is used to develop overlays to form composite special resource, hazard or development suitability maps. The mapping system utilizes a polygon format for inputting data. The program automatically converts from this format to a grid representation for data manipulation.

Li, Shanholtz, Contractor and Carr, 1977 (25). This model involves discretization of a drainage basin into hydrologic response units (HRU's) based on soils, land use, and physiographic features. Precipitation excess is generated using the Holtan equation and flow is routed using a finite element solution of the kinematic wave equations. A grid method and digital processing are used to derive HRU's from overlays of soil and land use maps. Finite elements and HRU boundaries do not coincide and the program must therefore derive a weighted precipitaion excess for each element based on HRU's within the element before flow routing is done.

Gupta and Solomon, 1977 (13). In this model, a basin is conceptualized as being composed of a set of finite-sized grids with each grid homogeneous in physical characterstics. The data base contains a series of digitized maps of physiographic data, time series data, and location of meteorological and hydrologic stations. Map data are digitized by using a polygon method. A series of computer programs transpose this data into grid data.

Rainfall excess is computed for each grid using the Holtan equation. A surface and sub-surface water balance is done, and flow is routed using the Muskingum method.

Davis, 1978 (2). Spatial data management techniques for comprehensive flood-plain studies are described in this paper. A grid cell format is used to store data such as existing and future land use, physiographic data, hydrologic sub-basins, and environmental habitats. Utility programs access files and create input for programs used in flood hazard evaluation, flood damage analysis and environmental assessments.

Jett, Weeks and Grayman, 1979 (23). This paper describes an application of the ADAPT triangular data base to hydrologic modeling using several alternative rainfall-runoff models. The paper emphasizes that since GIS's provide detailed physical modeling of drainage basins, an analysis doesn't have to be constrained to acquiring data for a specific model. Instead, one can select the most appropriate model based on the type of investigation. Hydrologic models developed for use with ADAPT range from simple unit hydrograph models with unit hydrograph parameters derived from average basin characteristics, to detailed routing models which compute excess for each triangular element and route flow through both overland and stream networks.

Thomsen and Striffler, 1980 (33). This report describes a watershed information system which is used to continuously simulate snowpack processes and to generate stream flow forecasts. The system utilizes remote sensing data to

periodically update the simulation. A grid approach is used to create a set of overlays containing data on elevation, aspect, vegetation and soils. Two programs derive parameter decks for water yield and stream flow models using these overlays. The water yield program does water balance, snow accumulation and melt calculations. Output from this model drives the stream flow model which uses a Darcy-type equation and the continuity equation to calculate lateral flow. Deep seepage and baseflow are treated empirically. The model does not consider Hortonian-type infiltration because infiltration rates on terrain simulated by the model are generally much greater than any snowmelt or rain event.

Eli, Palmer and Hamrio, 1980 (5). This paper describes an application of ADAPT to high resolution modeling of an abandoned strip mine in West Virginia. The model consists of 270 triangles some of which are a fraction of an acre. The object of the study is to model the micro-topography of the site including spoil piles, access roads, benches and drainage courses. The paper demonstrates how ADAPT can be an efficient method for increasing hydrologic model resolution. It also demonstrates how this increased resolution allows accurate modeling of flow direction and concentration of runoff.

Eli, 1981 (7). This paper proposes a combination of ADAPT with the Hewlett concept of variable source areas of runoff for continuous or single event modeling on small watersheds. The paper describes the previous application of ADAPT for surface mine hydrology in West Virginia and suggests modifications to

original routines that will enable continuous modeling. It also outlines modification of the overland routing scheme to incorporate the concept of contributing area. A series of "runoff bands" which bound the contributing area are determined by a new set of decision rules. The paper describes how the runoff bands can be utilized in erosion and sediment yield computations. It also describes how below ground surfaces can be represented by assigning more than one elevation to each triangle vertex. These additional surfaces can be used to do mass balance for continuous hydrologic modeling.

Eli and Paulin, 1981 (6). This paper describes applications of TIN type GIS's to runoff and erosion-sedimentation modeling. It demonstrates how GIS's can be used to derive input for existing hydrologic models such as SCS TR-20. It also suggests an alternative method for computing overland flow lengths. Instead of constructing centroid-to-centroid connecting lines, the downslope vector becomes the actual flow path. Flow direction changes as triangle boundaries are crossed and triangle slopes change. The paper suggests that present applications do not take advantage of the spatial resolution available in these models. It recommends using the principles developed for "cascading planes" to develop a flow model which is more compatible with GIS's. The paper also mentions a microcomputer compatible TIN GIS called "GEOSPHERE" which is being developed by Eli for small-watershed, high-resolution environments.

La Garde, 1982 (24). This report describes a rainfall-

runoff model which employs a polygon-to-grid GIS to store data. The report provides step-by-step instructions for creating a data base and running the model. Soil, land use and topographic data are input using a polygon method. Auxiliary programs convert and process the data into grid format to create a GIS. Rainfall excess is computed for each grid using CN's. A lag equation which is a function of CN and surface slope is used to allocate flow between grids. Lag divided by time step defines the fraction of flow in temporary storage that will be removed to the lowest downstream grid. A flow history can be developed for each grid.

Grayman, Males, Gates and Harris, 1982 (12). This paper describes applications of ADAPT to urban hydrology. The advantages of ADAPT for modeling urban hydrology are outlined including its ability to provide a continuous model of topography. The paper describes how ADAPT can be used to model both natural and man-made networks. It illustrates application of ADAPT to urban hydrology with example projects in Ohio, Wyoming and Pennsylvania. The Ohio study involved detailed rainfall-runoff/non-point source pollution modeling of twelve northeastern Ohio sub-basins. In the Wyoming study, the issue was determination of the impact of proposed future development on an existing sewer and drainage system. In Pennsylvania, the study involved rainfall-runoff modeling and generation of flood plain maps for the main stream drainages.

Eli and Paulin, 1983 (8). This paper describes a sensitivity analysis of a rainfall-runoff model consisting of the

ADAPT system and a linear res... .r-linear channel routing model. CN is used to generate excess precipitation. The number of triangular elements is varied to test sensitivity of the outflow hydrograph to terrain model resolution. Lag-coefficients are also modified to determine the effect on model results. Using three different model resolutions of the basin, it is demonstrated that as the number of triangles is increased, average link slopes increase, maximum triangle slopes increase, average triangle areas decrease, and number of stream links increase.

It is also demonstrated that model results are a function of lag coefficients chosen. In cases where the proportion of lag assigned to the linear reservoir is 50 percent or less, the high resolution model peaks sooner and higher than the low resolution model. The situation reverses when more than 50 percent of the lag is assigned to the linear channel. It is concluded that for "realistic" values of the lag coefficients, the model does not require a high resolution representation to yield acceptable results.

Heggen, 1983 (20). This GIS employs a grid representation of the watershed. Each grid is described by elevation, soil and cover characteristics, and channel descriptions if applicable. The CN method is used to define surface infiltration. Channel infiltration (important in New Mexico) is estimated using an empirical expression developed for New Mexico. Surface runoff is described using Manning's equation. Effective slope and slope

length are derived by empirical relationships and by field estimates respectively. The direction of channel flow is computed by a partitioning routine which divides outflow by grid based on relative grid elevations. A set of channel hydraulic characteristics must be assumed to accomplish this.

Eli, 1983 (9). This paper describes the application of GIS's to planning, design and analysis of coal mines. It presents an overview of available GIS's and discusses advantages and disadvantages of each. A description of a new TIN based system called "HYGIS" (Hybrid Geographic Information System) is presented in the paper. This system uses a TIN to represent three-dimensional surfaces above and below ground. Two-dimensional polygon overlays containing attribute information can be created independent of the TIN's. A three-dimensional grid cell system is incorporated to aid in locating specific areas of the data base. Grid cell structure also aids in connecting the multiple TIN surfaces and overlays. The system is used to produce various maps, including projections and cross-sections of surface and sub-surface structures. Engineering data including lengths, areas and volumes can also be calculated.

HEC, 1983 (16). This document describes the procedure for developing HEC-1 input data using a grid cell GIS. Data is entered in a grid format using a program called "BANK." Verification of input is accomplished with program "RIA" which displays stored data using line printer graphics. Program "HYDPAR" is the interface between the grid cell GIS and the rainfall-runoff model (HEC-1). HYDPAR derives loss rate and unit

hydrograph parameters from the GIS. Results are output to a file which can be automatically transferred to HEC-1. SCS CN and percent imperviousness are derived using HYDPAR as are the SCS and Snyder unit graph coefficients. The SCS unit graph lag is computed using an equation in which the lag is a function of average basin slope and CN. Slope and CN are input for each grid. Snyder's lag is a function of stream lengths, stream slope and percent imperviousness. All these values must be manually derived and input to run HYDPAR.

McKim, Unger, Merry and Ganthier, 1984 (26). The objective of this study was to integrate remotely sensed land cover data with a hydrologic model developed for the Saginaw River Basin in Michigan. The data base developed was compatible with the HEC Spatial Analysis Methodology (HEC-SAM) software (2). Two computer programs were used to classify land use from the Landsat images. The resulting 1.1 acre Landsat land cover classification was converted to 40-acre grid cells using an aggregation scheme. HEC-1 optimization methods were used to derive Clark and Snyder unit graph parameters. For seven gaged sub-basins, multiple linear regression was then used to develop relationships between unit graph parameters and the land use classification for each sub-basin.

Hong and Eli, 1985 (21). This paper describes a rainfall-runoff model which accounts for both the overland flow-interflow and the infiltration-exfiltration processes. The model uses a TIN-type topographical model. Flow direction, slope, hydrologic

and topographic characteristics are stored in the DTM. Using this information, a program determines the series of elements which contribute to each stream segment. Each series is treated as a set of planes over or through which flow passes. Water is routed continuously through a combination of overland flow and interflow from the top element down to the stream segment. Kinematic Wave routing is used to describe overland flow routing while Darcy's law is used to describe interflow. The storage-discharge history of each element is based on conservation of mass.

4. TESTING PROGRAM

This section of the report describes the procedures and results of the testing program. As mentioned previously in the objectives section, the major goals of this study are: 1) to test the ability of HEC1-ADAPT to model rainfall-runoff on ungaged basins; 2) to determine the effect of model resolution on the simulated outflow hy :ograph; and 3) to test the flexibility of the HEC1-ADAPT system.

To accomplish these goals, two drainage basins are used in the testing program. The first is Castro Valley, a predominately urban basin of 5.5 square miles located in the San Francisco Bay area. Potter Valley, the second, is an agricultural basin with an area of 92.2 square miles located in the Russian River basin in northern California. These basins were chosen because they represent a fairly wide range of geographic conditions. Modeling these two basins should provide a good test of the flexibility and robustness of the HEC1-ADAPT methodology thus accomplishing the third goal of the study. Castro Valley is modeled using two resolutions to accomplish the second goal of the study. Potter Valley is modeled using one resolution.

Both basins are first modeled as if they are ungaged to accomplish the first goal of the study. Results of this modeling are highly dependent on the adopted model parameters. Thus, it is important to chose the appropriate curve number to use with a given combination of land use and soil type and the appropriate roughness and percent imperviousness to associate with a given

land use. Results of the ungaged modeling effort are compared with observed data.

The higher resolution Castro Valley model and the Potter Valley model are then calibrated using several observed flood events. Results of the calibrations are compared with historical data and with hydrographs generated using Clark unit graphs derived by HEC-1 optimization methods. The models are then validated using other historical flood events. A sensitivity analysis is performed on the calibrated models of the two basins. Results are tabulated and discussed.

Lastly, modifications to the models are examined and some preliminary runs are used to demonstrate the effect of these changes on simulation results. These results are then discussed.

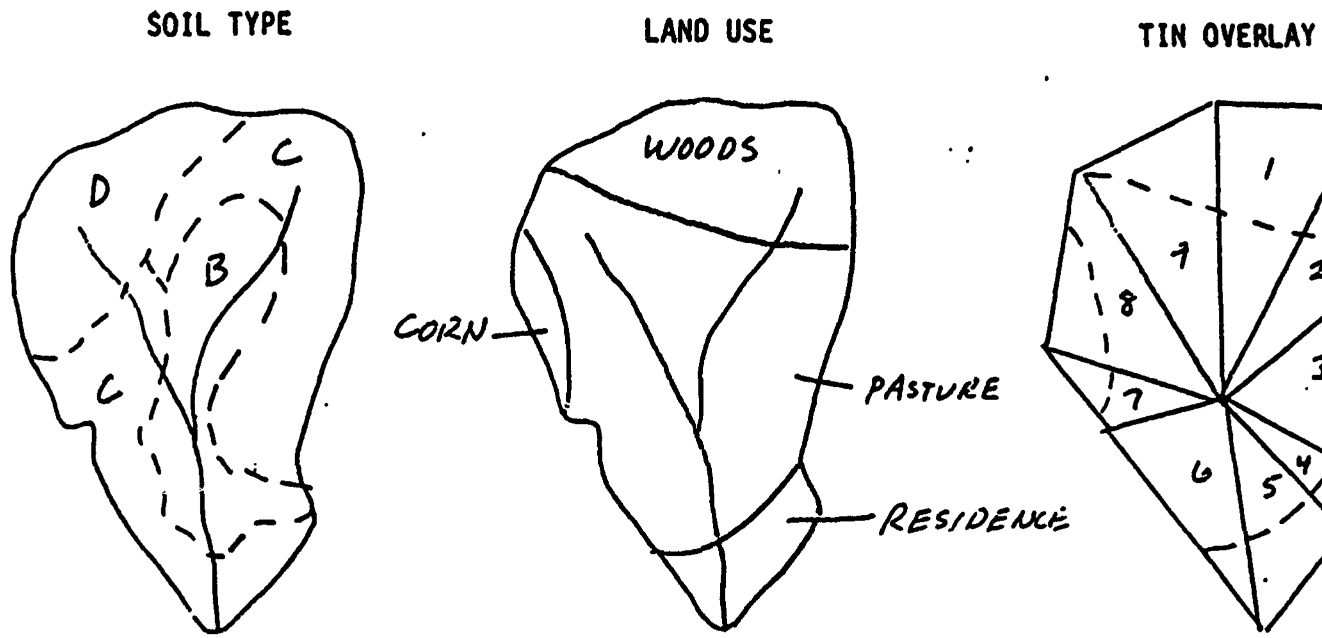
5. ANALYSIS AND RESULTS

5.1 Castro Valley

The representation of topography in the HEC1-ADAPT system is probably the most important feature of the method since derivation of all the HEC-1 input is dependent on it. In this testing program, the DTM is not modified to incorporate the land use and soil type boundaries. Instead, this information is input on a triangle-by-triangle basis with each triangle containing a mix of the various soils and land uses (see Figure 8). The interface program, HECAD, determines a weighted average land use and soil type for each triangle based on the percentages in each triangle. This approach is used throughout the testing program.

Castro Valley was the first basin modeled using HEC1-ADAPT. This basin was used because of its small size (5.5 square miles) and because of the availability of all necessary data at the offices of the Hydrologic Engineering Center. Two models of Castro Valley were developed. The first model consisted of 39 triangles (see Figure 9). Average triangle area for this model was about 90 acres.

Because each of the models in this testing program is first developed assuming the basins are ungaged, the appropriate methods for computing and transforming rainfall excess are dependent on available data and on basin characteristics. HEC1-ADAPT provides two methods for computing rainfall excess: the SCS CN method, and the initial/uniform loss method. In the uncalibrated models developed for this testing program, CN's are



Triangle	Corn	Woods	Pasture	Residence
1		60%	40%	
2		30%	70%	
3			100%	
etc.				

FIGURE 8 SOIL AND LAND USE TRIANGLE INPUT METHODOLOGY

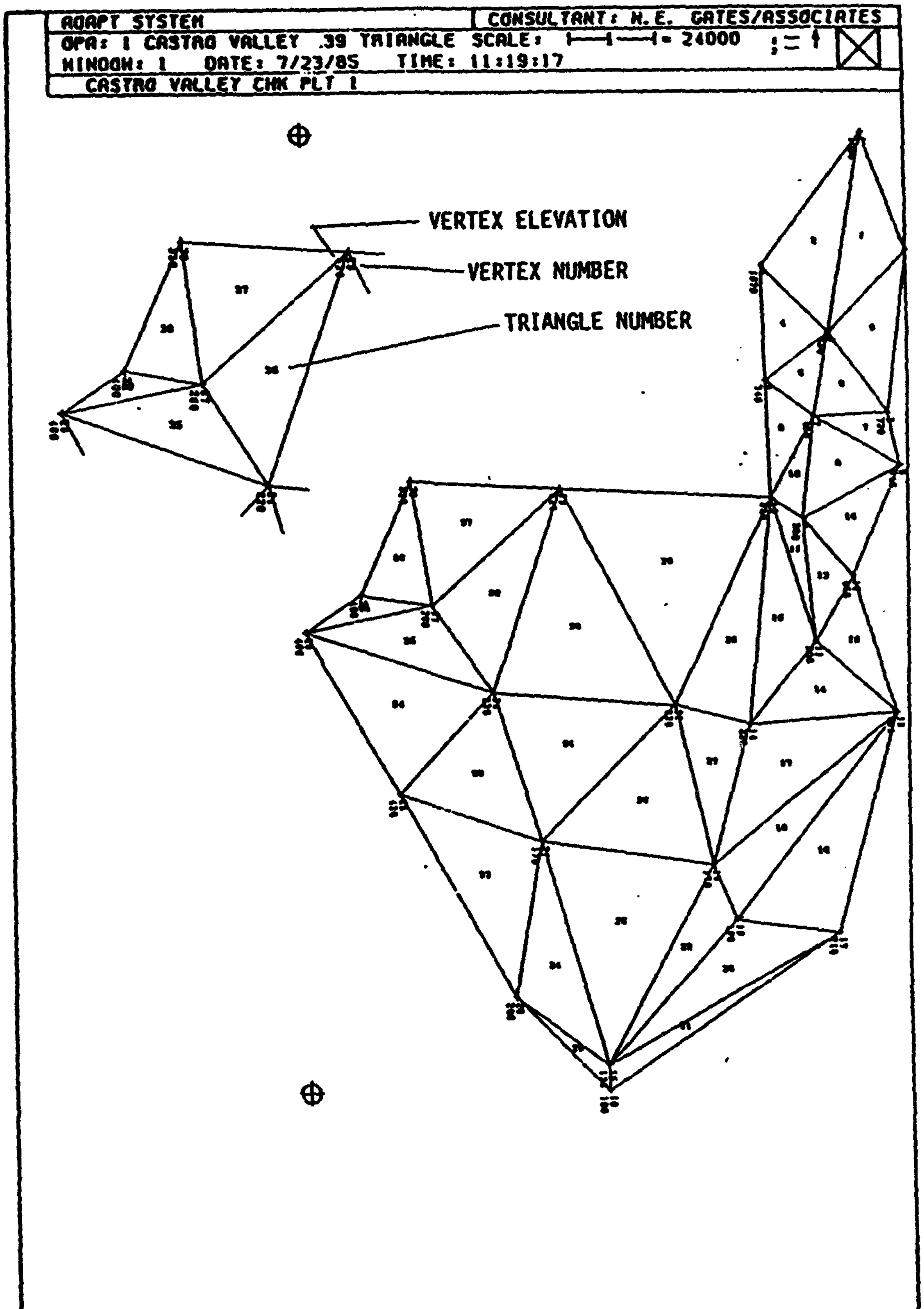


FIGURE 9 CASTRO VALLEY 39-TRIANGLE TIN

used to model excess because CN's can be related to soil type and land use. A CN adjustment subroutine automatically adjusts CN's based on the season and antecedent precipitation entered by the user. Since the Castro Valley is predominately urban, the Kinematic Wave model is used for both overland and channel routing. The land use and soil data used to model Castro Valley were taken from a previous HEC study of Castro Valley (19). Table 1 tabulates land use, soil type, percent imperviousness and CN used in the uncalibrated model of Castro Valley.

Given the geographic information stored within the model and the calibration data input by the user, HECAD derives the HEC-1 model coefficients and generates HEC-1 input data. The HEC-1 input data generated by HECAD for the 39-triangle Castro Valley model are on file at the HEC.

HEC-1 was run using this input data. Figure 10 shows the computed and observed hydrographs for the Jan 16, 1973 storm event. It can be seen by comparing these two hydrographs that the observed hydrograph peaks sooner and is quite a bit more peaked than the computed hydrograph. The observed hydrograph peak is about 2.3 hours before the computed and is about 13 percent greater. Runoff volumes are similar. Table 2 gives a tabulated comparison of computed and observed hydrographs.

The greatest difference is in the hydrograph timing. Many things could be affecting the timing. For example, the model may not adequately represent the basin, the input parameters may be inappropriate, or the temporal and areal distribution of precipitation may not be representative. To test the adequacy of

TABLE 1

CASTRO VALLEY LAND USE AND SOILS DATA

LAND USE	CURVE NUMBER HYDROLOGIC SOIL GROUP A	B	C	D	PERCENT IMPERVIOUSNESS
Natural Vegetation	39	61	74	80	0
Low Density Residential	57	72	81	86	30
Medium Density Residential	61	75	83	87	40
High Density Residential/Commercial	82	88	92	94	75

Source: HEC, undated. Oconee Style Hydrology Workshop. Urban Hydrology Cource Workshop for Castro Valley.

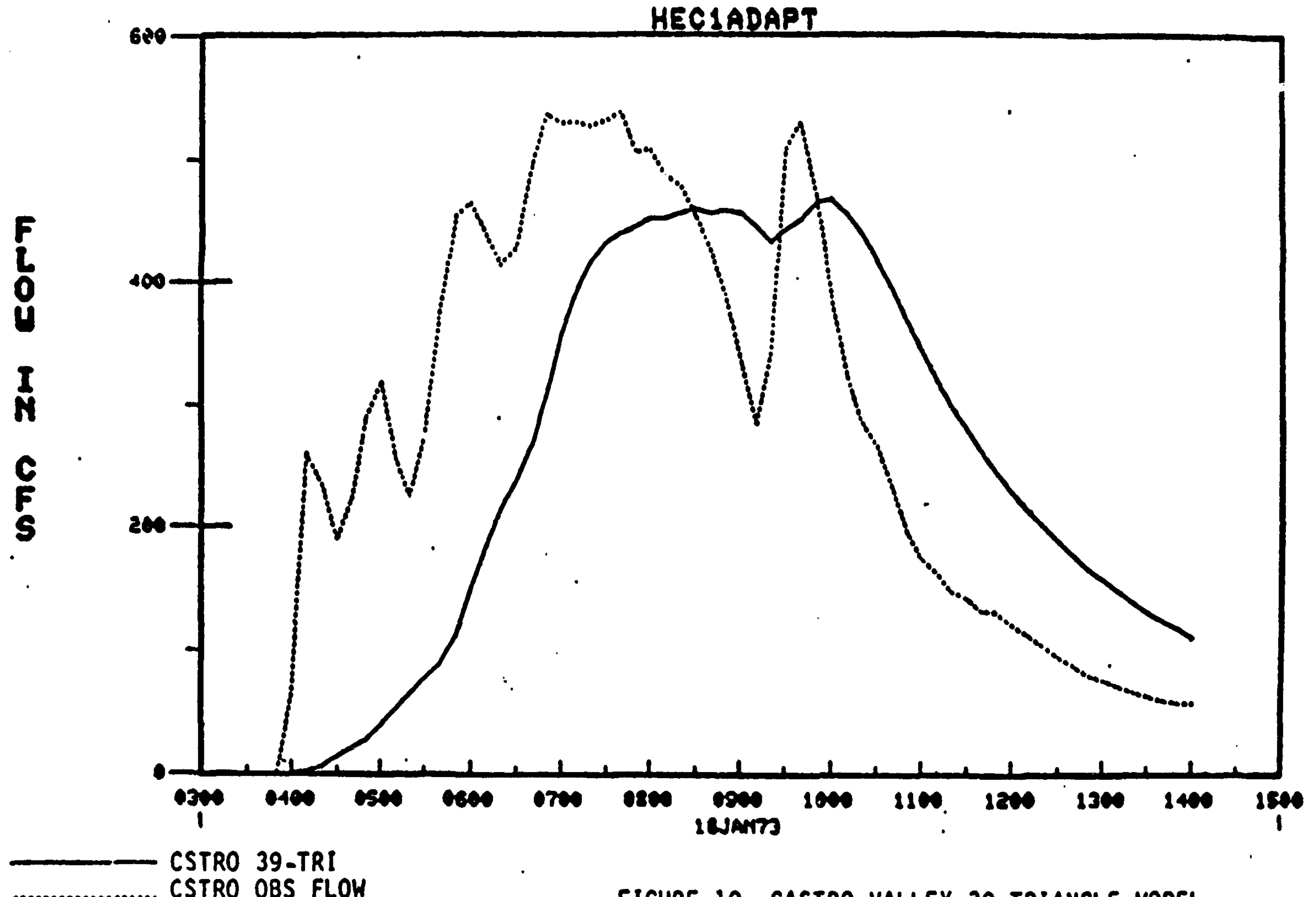


FIGURE 10 CASTRO VALLEY 39-TRIANGLE MODEL
UNCALIBRATED JANUARY 16, 1973 EVENT

TABLE 2

COMPARISON OF COMPUTED AND OBSERVED HYDROGRAPHS
CASTRO VALLEY 39-TRIANGLE MODEL
UNCALIBRATED JANUARY 16, 1973 EVENT

	SUM OF FLOWS (cfs-10min)	EQUIV. DEPTH (in)	MEAN FLOW (cfs)	TIME TO CENTER OF MASS (hrs)	PEAK FLOW (cfs)	TIME TO PEAK (hrs)
Computed Hydrograph	16105	0.749	248	6.22	467	6.67
Observed Hydrograph	17877	0.832	275	4.91	537	4.33
DIFFERENCE	-1772	-0.082	-27	1.31	-70	2.33
PERCENT DIFFERENCE	-9.91	-9.91	-9.91	26.72	-13.08	53.81

the 39-triangle model and to investigate the impact of using a higher resolution model, the 82-triangle Castro Valley model was developed. This second Castro Valley model is described in the next section.

5.1.1 Castro Valley 82-triangle Model

Eighty-two triangles were used in the second Castro Valley model to attain a higher degree of accuracy in the topographic representation. Average triangle area is about 45 acres which is about half that of the 39-triangle model. Figure 11 shows the 82-triangle representation. Figures 12 and 13, respectively, show contour plots developed for the 39- and 82-triangle models using the graphics capability of HEC1-ADAPT. One can see by comparing these plots that the 82-triangle model has some steeper slopes. This model also adds two of the smaller tributaries to the representation of the channel system.

Again, the basin is first modeled as if it were ungaged. Thus, the only change between the first and second Castro Valley models is the topographic representation. The calibration parameters (CN's, roughnesses) remain the same for the initial runs. The 82-triangle model is later calibrated using several historical events. The 39-triangle model is not calibrated.

The effect of this higher resolution is apparent in a comparison of the two hydrographs computed using the different models. Figure 14 shows the 39- and 82-triangle model hydrographs and the observed hydrographs for the January 16, 1973 storm. Table 3 gives a tabulated comparison of the two models. The 82-triangle model appears to concentrate runoff faster than

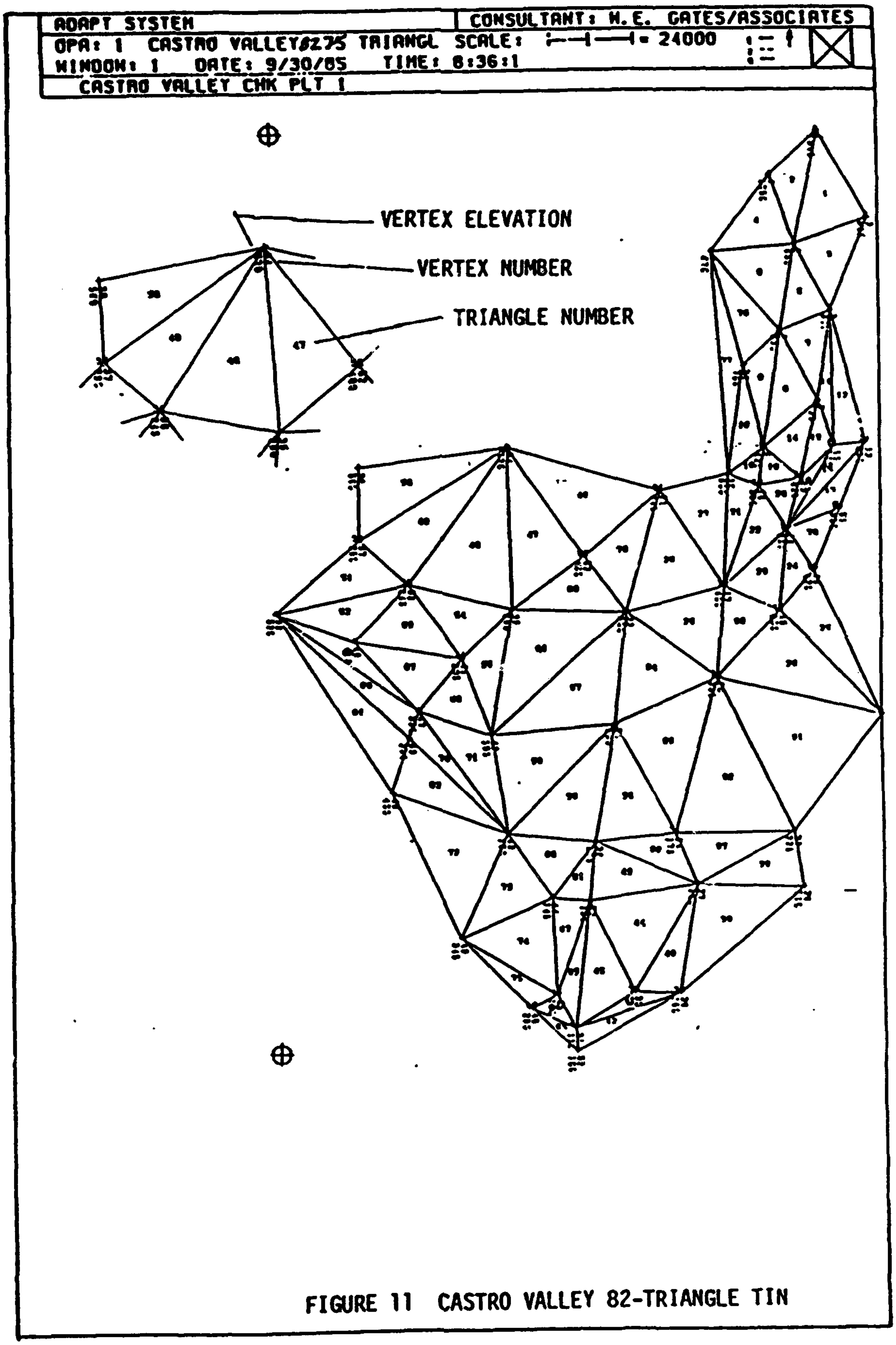


FIGURE 11 CASTRO VALLEY 82-TRIANGLE TIN

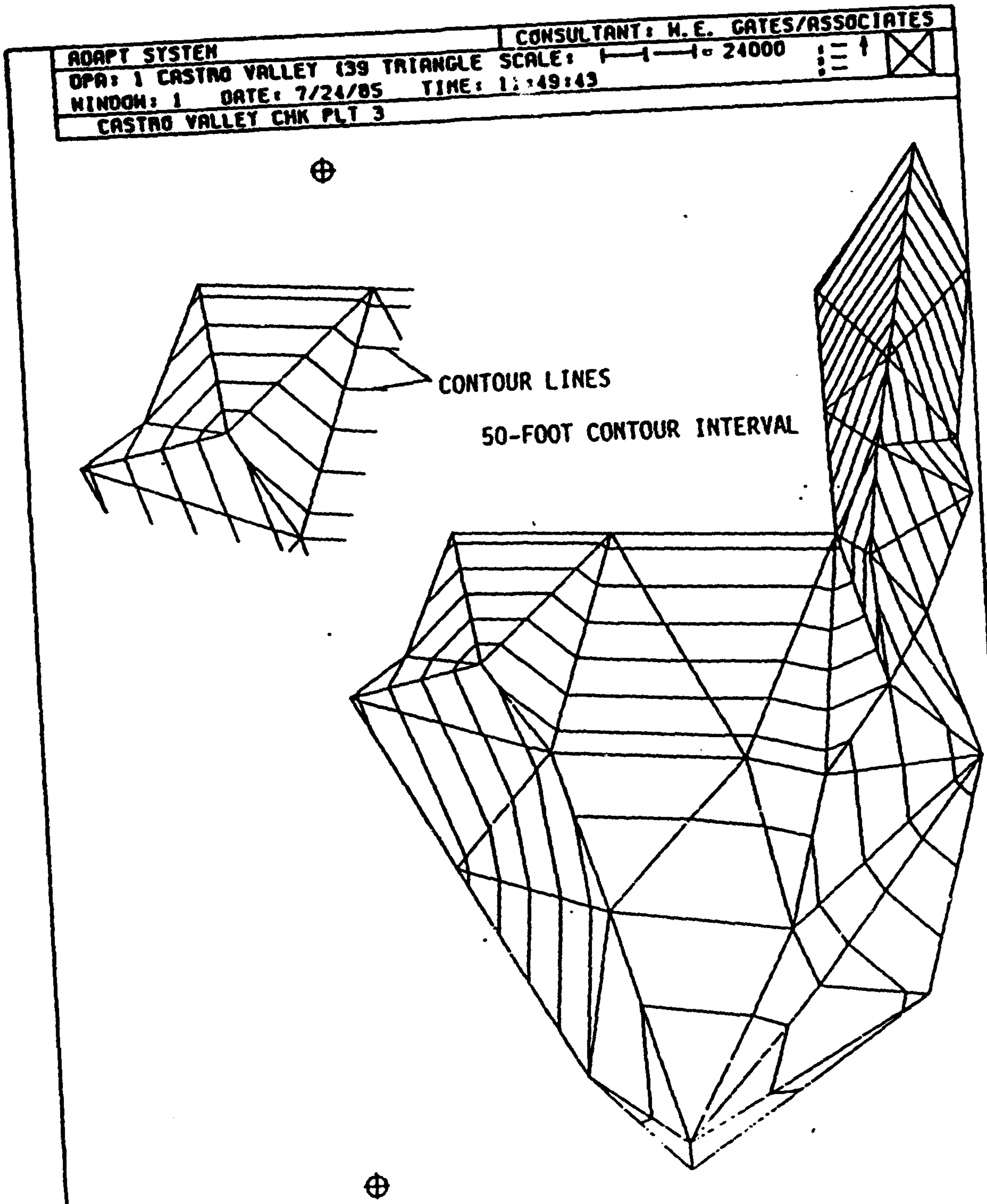


FIGURE 12 CASTRO VALLEY 39-TRIANGLE MODEL CONTOUR PLOT

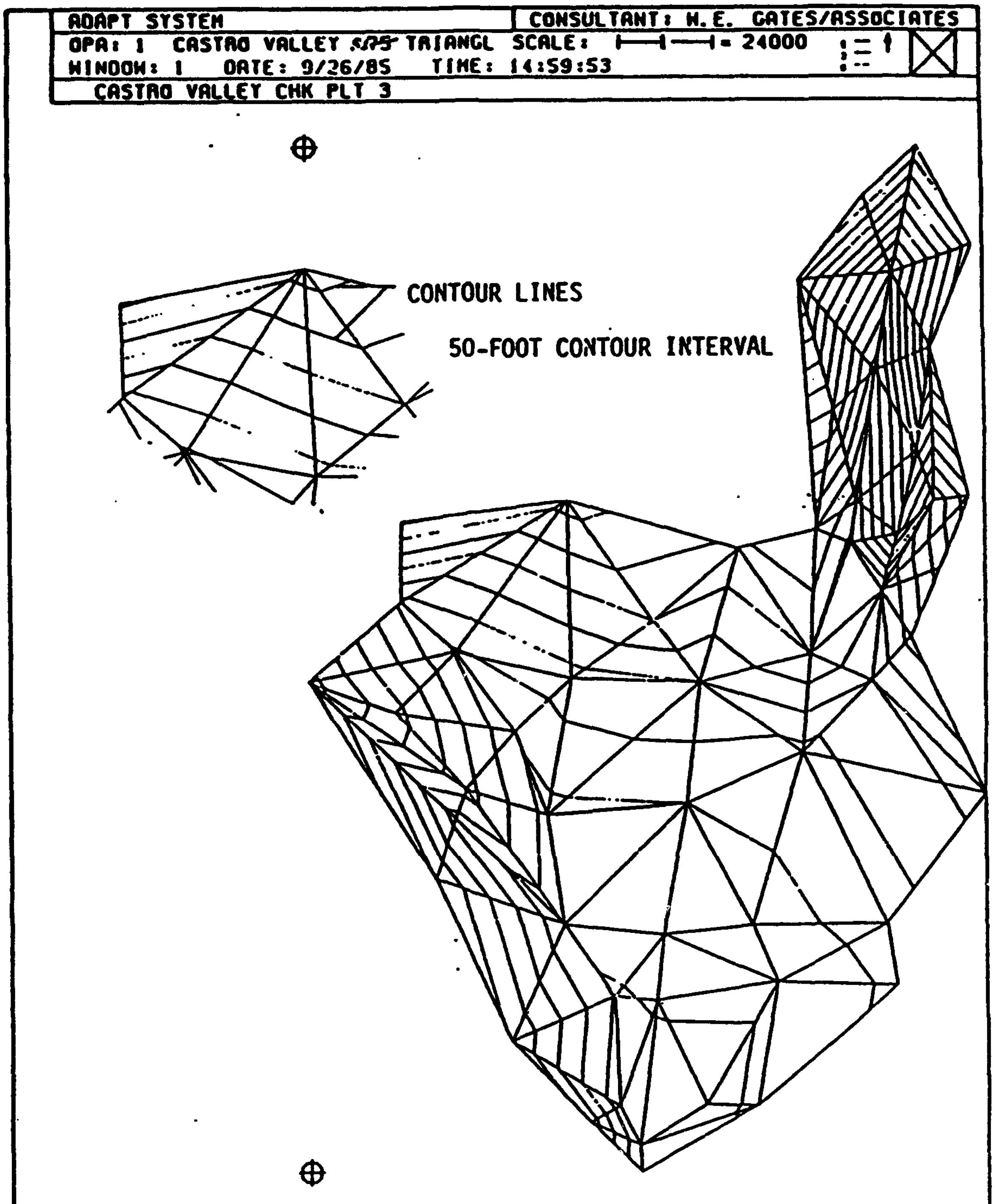


FIGURE 13 CASTRO VALLEY 82-TRIANGLE MODEL
CONTOUR PLOT

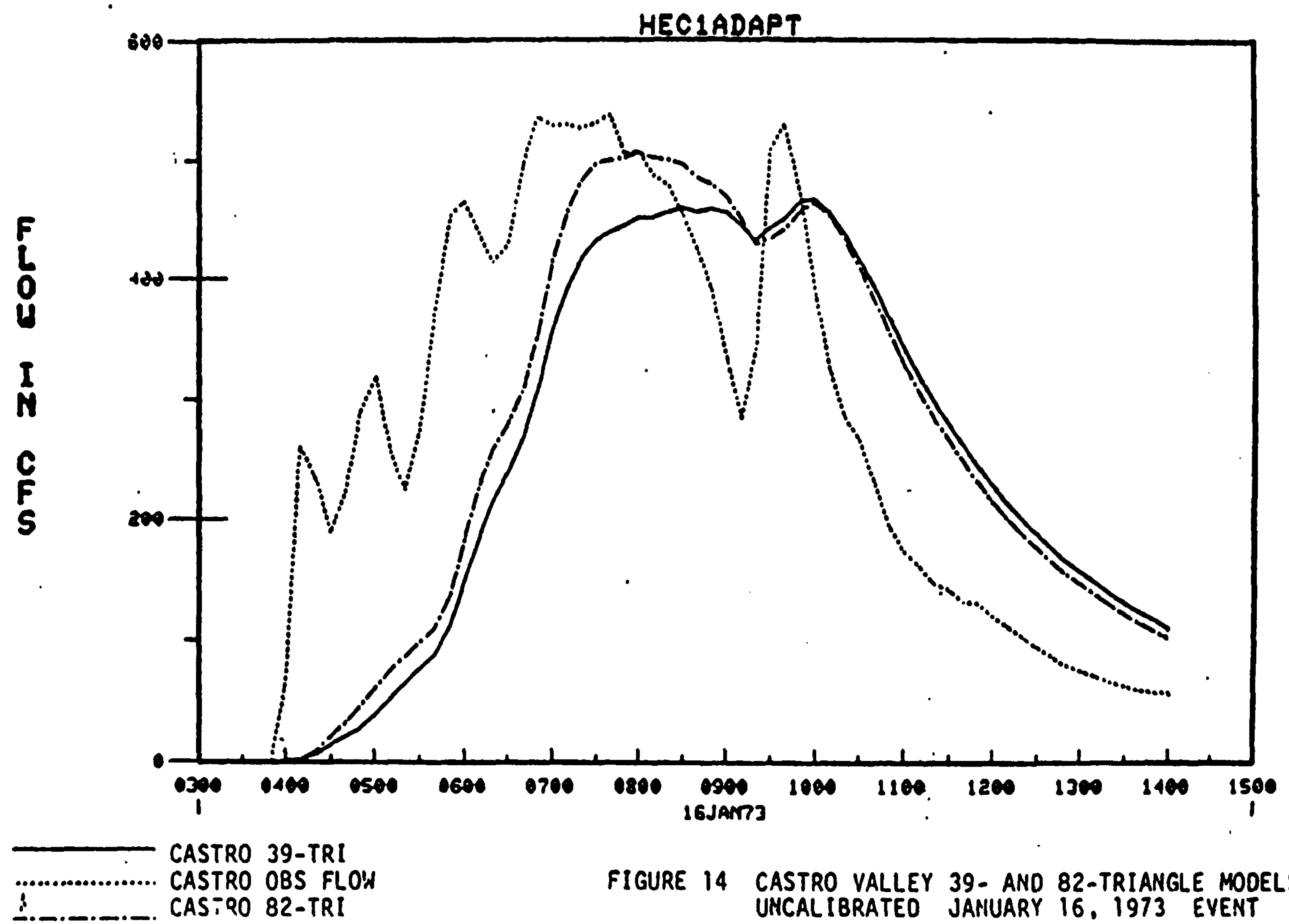


FIGURE 14 CASTRO VALLEY 39- AND 82-TRIANGLE MODELS
UNCALIBRATED JANUARY 16, 1973 EVENT

TABLE 3

COMPARISON OF 39- AND 82-TRIANGLE CASTRO VALLEY
MODEL HYDROGRAPHS UNCALIBRATED
JANUARY 16, 1973 EVENT

	SUM OF FLOWS (cfs-10min)	EQUIV. DEPTH (in)	MEAN FLOW (cfs)	TIME TO CENTER OF MASS (hrs)	PEAK FLOW (cfs)	TIME TO PEAK (hrs)
39-Triangle Model	16105	0.749	248	6.22	467	6.67
82-Triangle Model	16871	0.763	260	6.03	506	4.67
DIFFERENCE	-766	-0.014	-12	0.19	-39	2.00
PERCENT DIFFERENCE	-4.54	-1.83*	-4.54	3.15	-7.71	42.82

* Discrepancy between sum of flows and equivalent depth is caused by slight differences in drainage area between the two models.

the 39-triangle model because of the steeper slopes and increased number of stream links. The 82-triangle model hydrograph has a steeper rising limb and a greater peak than the 39-triangle model hydrograph. The lag (center of mass to center of mass) of the 82-triangle model is also less than that for the 39-triangle model. Although the differences are not great, the results appear to agree with those obtained by Eli (8).

The 82-triangle model response is still quite a bit slower than that of the observed basin however. This is evident in the slower lag time and the smoothness of the computed hydrograph. The observed Castro Valley response is almost immediate as shown by the rapidly rising and falling limbs of the observed hydrograph. There is apparently little basin storage. Because the basin is predominately urban, much of it is drained by gutters and storm sewers and the present model has no direct ability to account for this. Since the volume of the runoff in the simulation run is comparable to the observed, calibration of the model is first approached by lowering roughness factors to get a quicker response to compensate for the unmodeled storm drainage system.

The impact of modifying channel and overland roughnesses is illustrated on Figure 15 for the January 16, 1973 flood. This model responds more quickly as is evident in the steeper rising limb, the smaller lag, and the spikiness of the hydrograph. One more flood event is simulated using this model and the results are shown on Figure 16.

The runoff volumes are low and the response slow in the

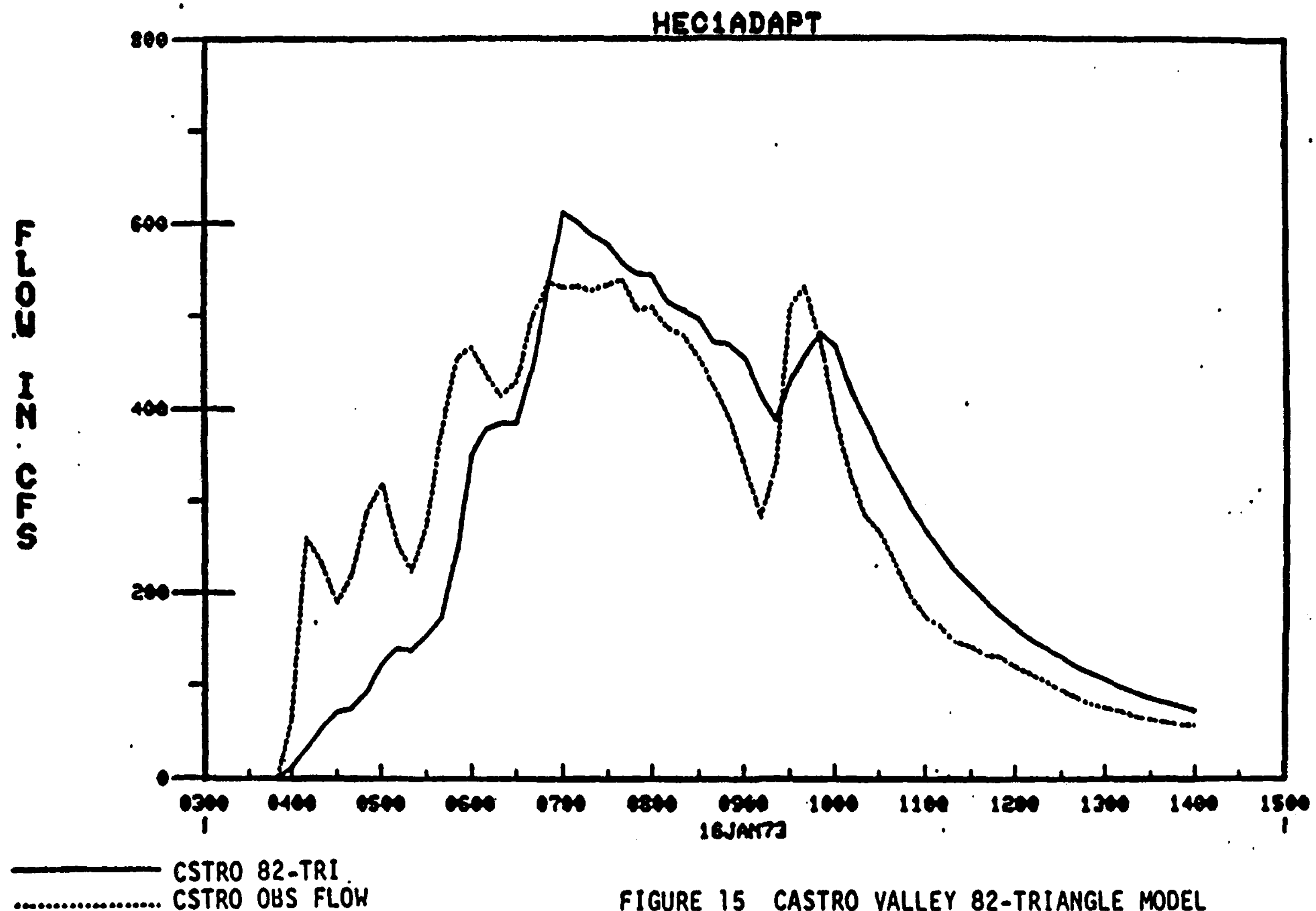


FIGURE 15 CASTRO VALLEY 82-TRIANGLE MODEL
MODIFIED ROUGHNESS JANUARY 16, 1973 EVENT

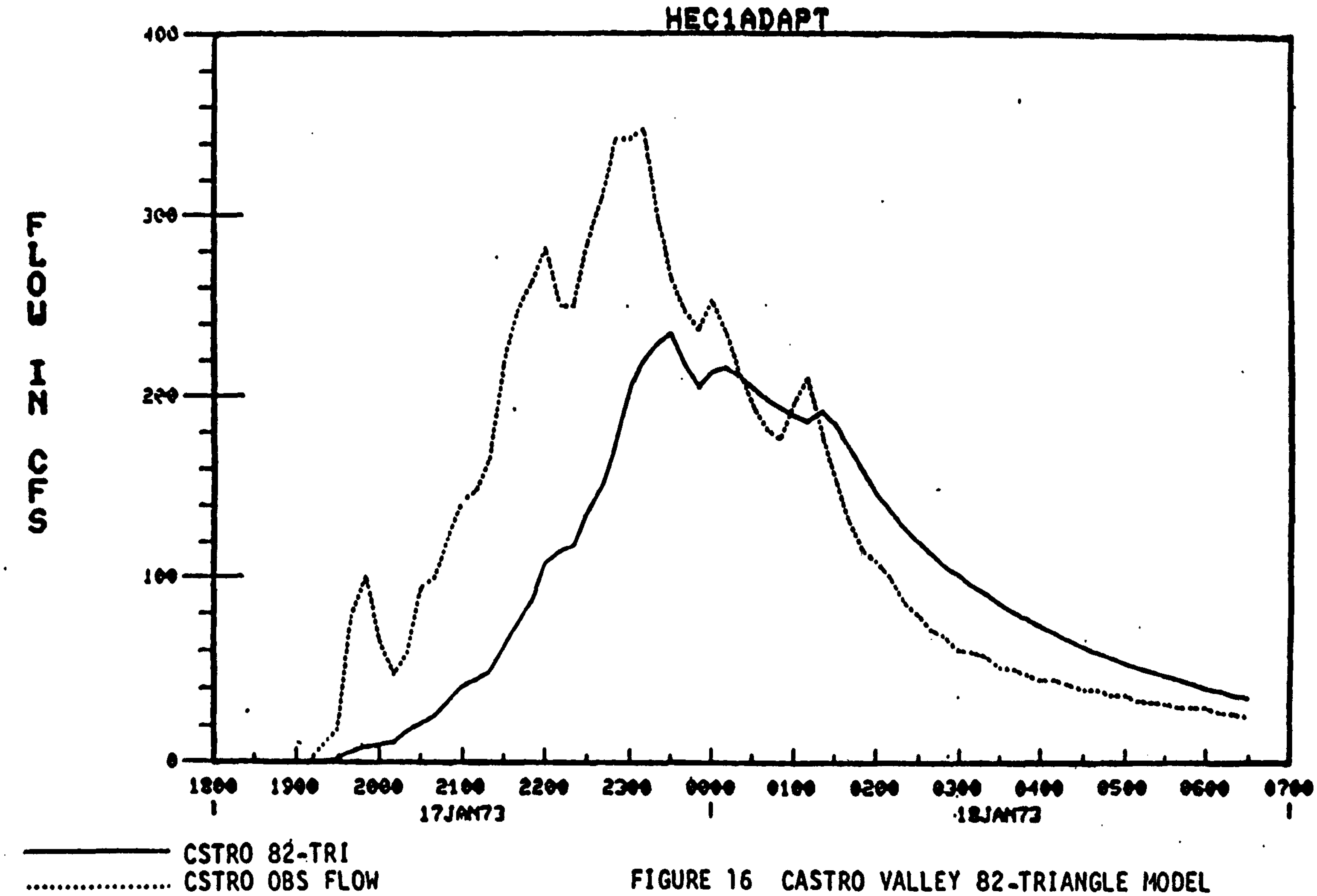


FIGURE 16 CASTRO VALLEY 82-TRIANGLE MODEL
MODIFIED ROUGHNESS JANUARY 17, 1973 EVENT

simulations of these events. To obtain a better calibration, the initial/uniform loss rate function is used to get both the correct runoff volumes and to shift more of the runoff volume to the rising limb of the hydrograph. Roughnesses are again adjusted until a reasonable match between the actual and computed hydrograph is obtained. The HEC-1 input data for the calibrated model are on file at the HEC. Results of this calibration are shown in Figures 17a and 18a. For comparison, hydrographs generated by the previous modified roughness model are also shown. Figures 17b and 18b compare the calibrated model hydrographs with hydrographs generated by HEC-1 using optimized Clark unit hydrograph parameters (19). Table 4 gives a tabulated comparison of the observed and calibrated model hydrographs for the January 16, 1973 flood event.

For the calibrated model, runoff volume is about seven percent less than the observed volume while the model lag (center of mass to center of mass) is about six percent greater than the observed lag. Model peak flow was about 28 percent greater than the observed peak flow.

One can see from Figures 17b and 18b that the HEC1-ADAPT simulations and the HEC-1 simulations using optimized Clark parameters produce hydrograph peaks, volumes and timing that are quite similar. After completing the calibration runs, both models are verified using the December 22, 1971 flood event. Figure 19 shows the hydrographs for these simulations while Table 5 compares the simulation results.

Although both models do a poor job of reproducing this

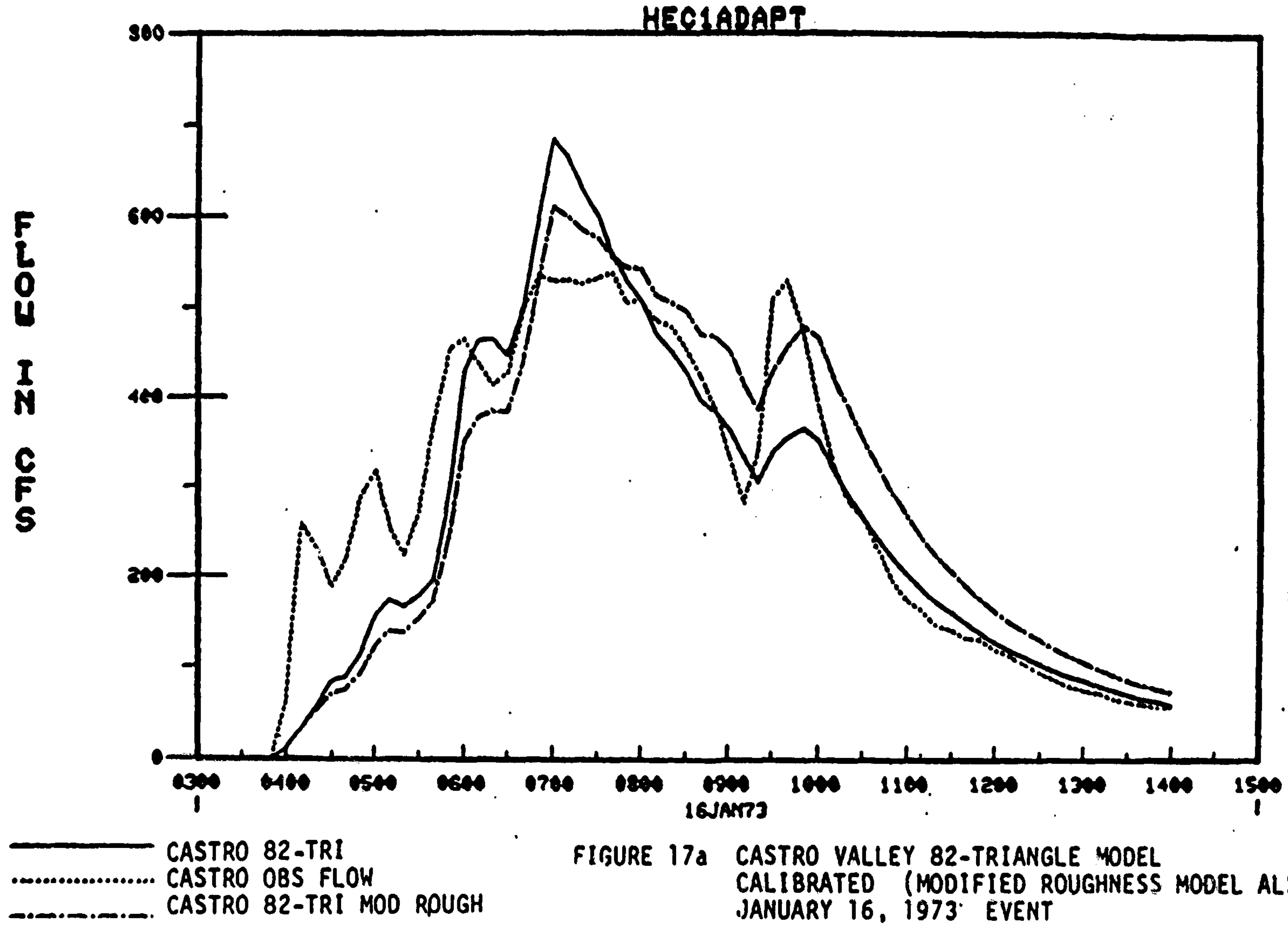


FIGURE 17a CASTRO VALLEY 82-TRIANGLE MODEL CALIBRATED (MODIFIED ROUGHNESS MODEL ALSO SHOWN) JANUARY 16, 1973 EVENT

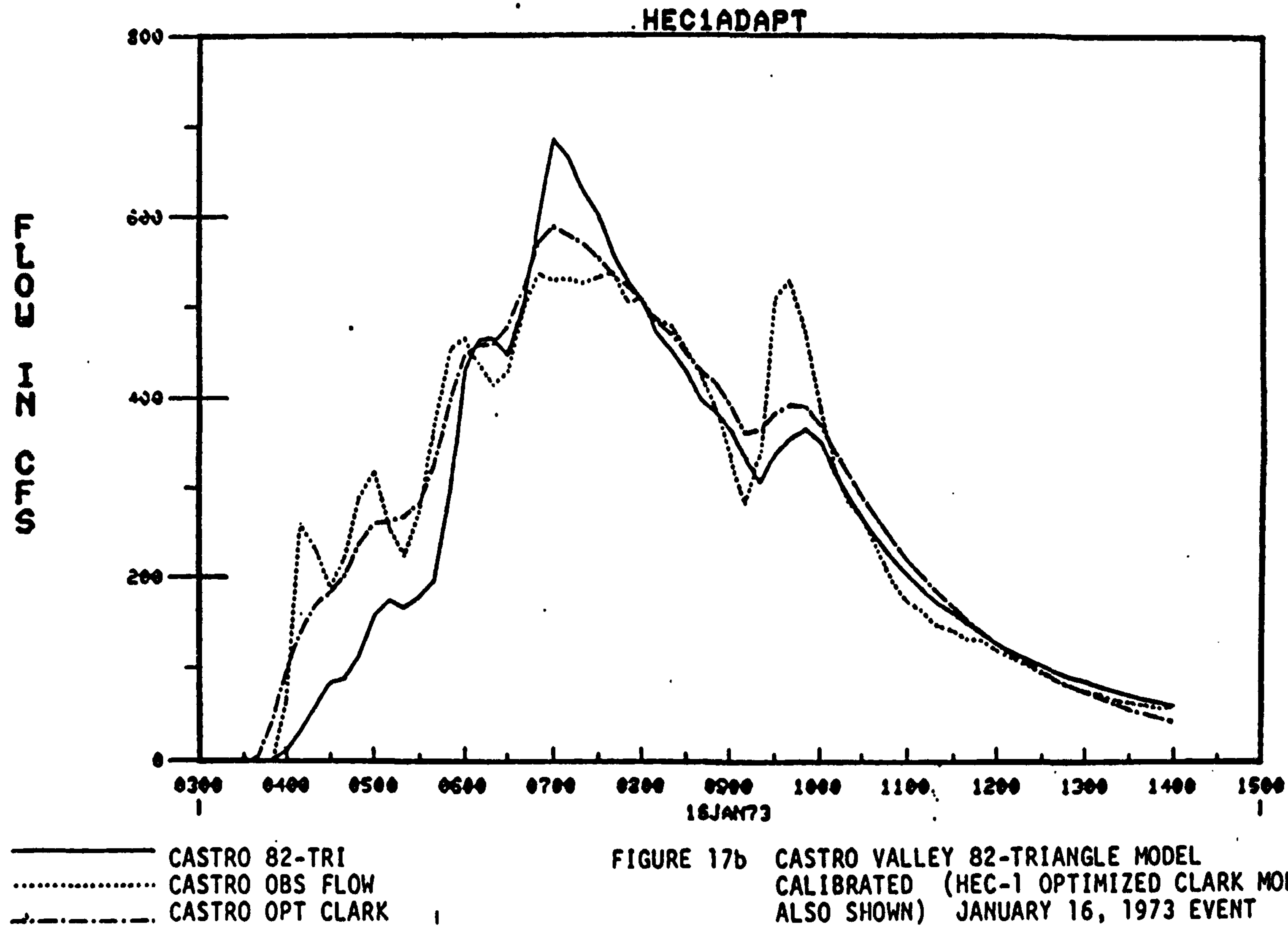
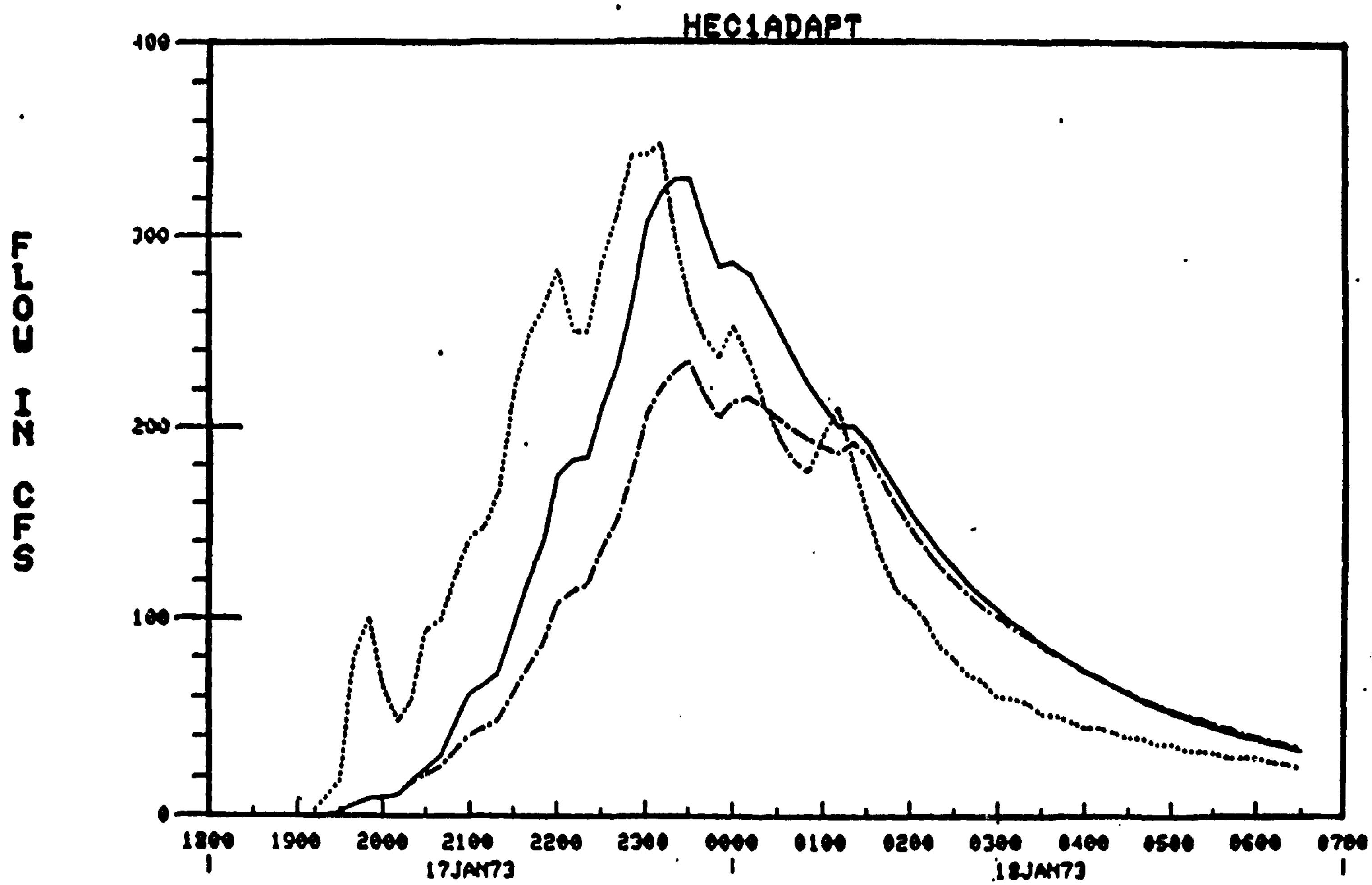
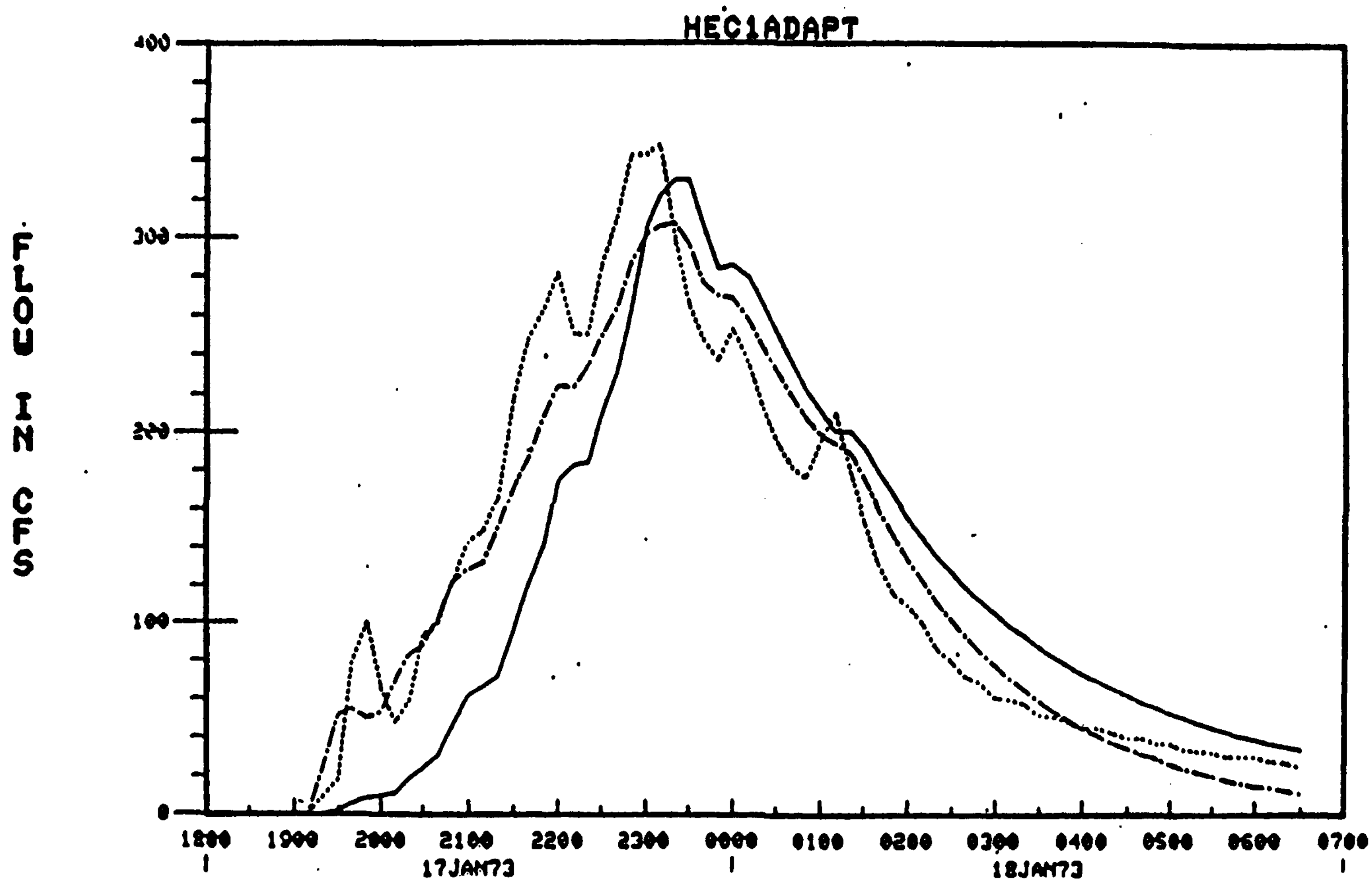


FIGURE 17b CASTRO VALLEY 82-TRIANGLE MODEL CALIBRATED (HEC-1 OPTIMIZED CLARK MODEL ALSO SHOWN) JANUARY 16, 1973 EVENT



CASTRO 82-TRI
CASTRO OBS FLOW
CASTRO 82-TRI MOD ROUGH

FIGURE 18a CASTRO VALLEY 82-TRIANGLE MODEL
CALIBRATED (MODIFIED ROUGHNESS MODEL ALSO SHOWN)
JANUARY 17, 1973 EVENT



CASTRO 82-TRI
CASTRO OBS FLOW
CASTRO OPT CLARK

FIGURE 18b CASTRO VALLEY 82-TRIANGLE MODEL CALIBRATED (HEC-1 OPTIMIZED CLARK MODEL ALSO SHOWN) JANUARY 17, 1973 EVENT

TABLE 4

COMPARISON OF COMPUTED AND OBSERVED HYDROGRAPHS
CASTRO VALLEY 82-TRIANGLE MODEL
CALIBRATED JANUARY 16, 1973 EVENT

	SUM OF FLOWS (cfs-10min)	EQUIV. DEPTH (in)	MEAN FLOW (cfs)	TIME TO CENTER OF MASS (hrs)	PEAK FLOW (cfs)	TIME TO PEAK (hrs)
Computed Hydrograph	16648	0.753	256	5.19	686	3.67
Observed Hydrograph	17877	0.809	275	4.91	537	4.33
DIFFERENCE	-1229	-0.056	-19	0.28	149	-0.67
PERCENT DIFFERENCE	-6.88	-6.88	-6.88	5.69	27.66	-15.47

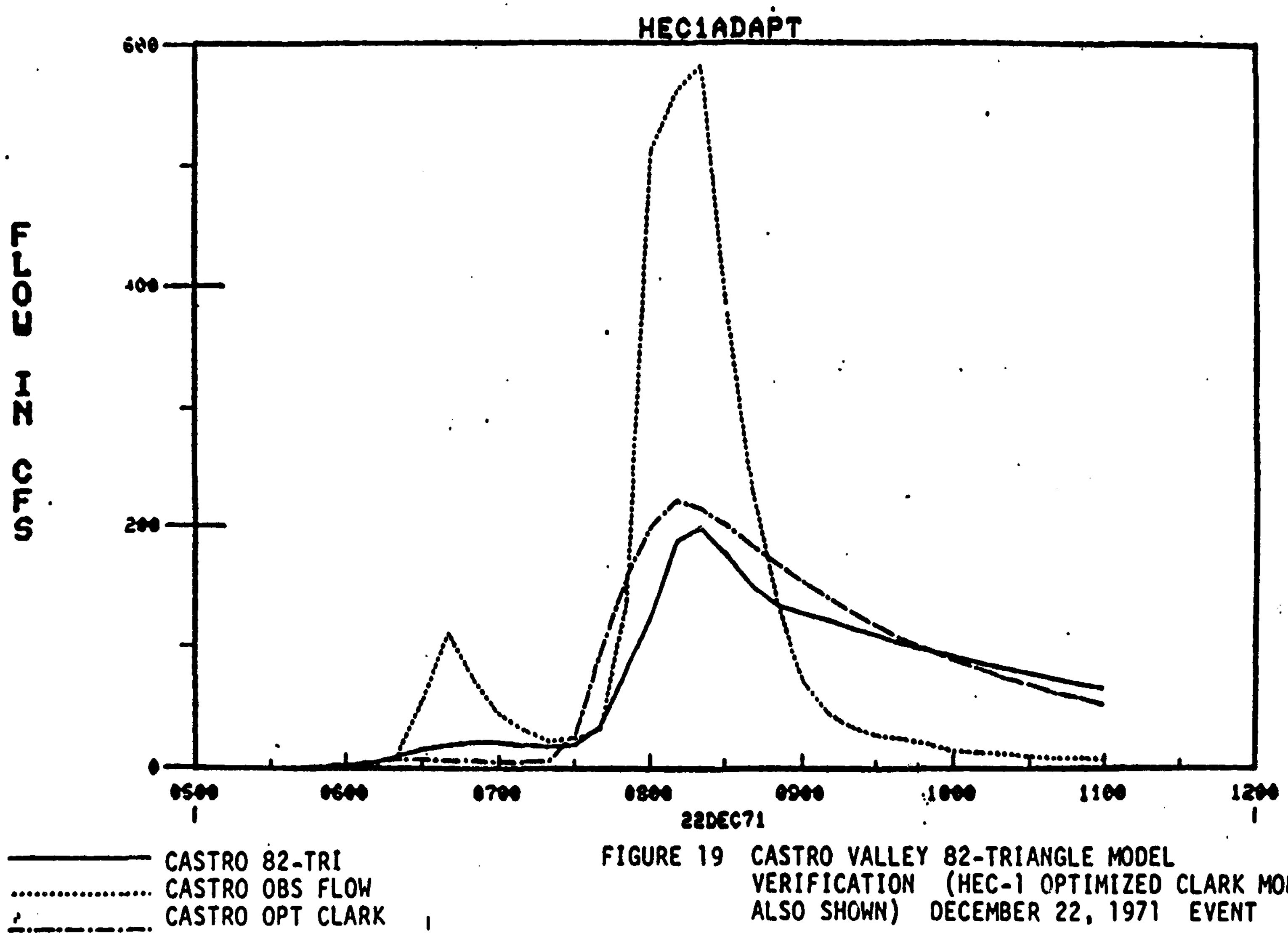


FIGURE 19 CASTRO VALLEY 82-TRIANGLE MODEL VERIFICATION (HEC-1 OPTIMIZED CLARK MODEL ALSO SHOWN) DECEMBER 22, 1971 EVENT

TABLE 5

COMPARISON OF 82-TRIANGLE MODEL AND HEC-1
OPTIMIZED CLARK MODEL HYDROGRAPHS
DECEMBER 22, 1971 EVENT

	SUM OF FLOWS (cfs-10min)	EQUIV. DEPTH (in)	MEAN FLOW (cfs)	TIME TO CENTER OF MASS (hrs)	PEAK FLOW (cfs)	TIME TO PEAK (hrs)
82-Triangle Model	2410	0.109	69	3.85	197	3.00
Optimized Clark Model*	2711	0.143	77	3.76	220	2.83
DIFFERENCE	-301	-0.034	-8	0.09	-23	0.17
PERCENT DIFFERENCE	-11.10	-23.78+	-11.10	2.39	-10.45	6.01
OBSERVED	3204	0.169	92	3.06	580	3.00

* Source: HEC, undated. Oconee Style Hydrology Workshop. Urban Hydrology Course Workshop for Castro Valley.
+ Discrepancy between sum of flows and equivalent depth is caused by slight differences in drainage area between the two models.

event, possibly due to innaccurate stream or rain gage data, the hydrographs produced by the two models are quite similar. From Table 5 it can be seen that simulated hydrograph parameters only vary by about 10 percent. HEC1-ADAPT appears to provide a physically-based methodology which simulates the rainfall-runoff process about as successfully as the HEC-1 optimized Clark method.

5.1.2 Sensitivity Analysis

In a sensitivity analysis, the major point that needs to be established is the relative sensitivity of state variables (like peak discharge) to changes in the values of model parameters (like surface roughness factors). The results of a sensitivity analysis give the modeler a "feel" for the effect inaccurate parameter estimation may have on the simulation. The definition below allows the modeler to decide what parameters have the most and the least impact on model results (27).

$$Sij=(\Delta Ci/Ci)/(\Delta Bj/Bj)$$

Where: Sij=sensitivity coefficient

ΔCi=change in state variable (e.g. discharge)

Ci =reference value of state variable

ΔBj=change in parameter (e.g. channel roughness)

Bj =reference value of parameter

All parameters are held constant except the one being studied to isolate the impact of the individual parameter. Using this approach, the sensitivity coefficients are computed and then compared directly to determine what parameters have the greatest impact on model results. Table 6 shows the results of the

TABLE 6

SENSITIVITY ANALYSIS
CASTRO VALLEY 82-TRIANGLE MODEL

PARAMETER	CASE (%)	PEAK DISCH (cfs)	LAG (hrs)	EQUIV DEPTH (in)	SENSITIVITY COEFFICIENTS $\frac{\Delta Q/Q}{\Delta B/B}$*	$\frac{\Delta L/L}{\Delta B/B}$*	$\frac{\Delta D/D}{\Delta B/B}$*
Overland Roughness	Ref.	686	5.19	0.753			
	+20	637	5.33	0.738	0.357	0.135	0.100
	+10	661	5.26	0.745	0.364	0.135	0.106
	-10	717	5.10	0.760	0.452	0.173	0.093
	-20	746	5.02	0.768	0.437	0.164	0.100
Channel Roughness	Ref.	686	5.19	0.753			
	+20	678	5.20	0.753	0.058	0.010	0.0
	+10	682	5.19	0.753	0.058	0.0	0.0
	-10	690	5.18	0.753	0.058	0.019	0.0
	-20	694	5.17	0.753	0.058	0.019	0.0
Initial/ Uniform Loss	Ref.	686	5.19	0.753			
	+20	624	5.23	0.688	0.452	0.039	0.432
	+10	653	5.21	0.719	0.481	0.039	0.452
	-10	720	5.16	0.789	0.496	0.058	0.478
	-20	756	5.14	0.831	0.510	0.048	0.518
Percent Impervious	Ref.	686	5.19	0.753			
	+20	729	5.14	0.812	0.313	0.048	0.392
	+10	705	5.17	0.778	0.277	0.039	0.332
	-10	667	5.21	0.724	0.277	0.039	0.385
	-20	645	5.23	0.695	0.299	0.039	0.385

* ΔQ – change in peak discharge
Q – reference value of peak discharge
ΔL – change in lag
L – reference value of lag
ΔD – change in equivalent depth
D – reference value of equivalent depth
ΔB – change in parameter (e.g. overland roughness)
B – reference value of parameter
$\frac{\Delta Q/Q}{\Delta B/B}$ – sensitivity coefficient for peak discharge

Note: reference values for state variables and parameters are from the calibrated model

sensitivity analysis for the 82-triangle Castro Valley model. From Table 6, it is seen that peak discharge and equivalent depth are most sensitive to estimates of loss rates while lag is most sensitive to estimates of overland roughness.

Castro Valley responds rapidly to rainfall because of its comparatively small size (5.5 square miles) and its urban character. All excess produced by the basin is transported to the basin outlet over a very short period of time. This rapid concentration of runoff is probably the reason simulated peak discharge is most sensitive to the estimates of the loss parameter.

Peak discharge is also very sensitive to estimates of overland roughness because of the direct impact of this parameter on the timing of runoff. The estimate of channel roughnesses is less significant for the peak for two reasons. First, the contribution of stream travel time to total travel time is proportionately less for small basins. Second, the channel roughness factors are small in magnitude to begin with. A 10 or 20 percent change in a smaller magnitude parameter will not affect the simulation as much as a 10 or 20 percent change in a larger magnitude parameter.

Percent imperviousness has a smaller impact on the peaks because the percentage of impervious surfaces is much less than the percentage of pervious surfaces for the basin.

Lag is most sensitive to estimates of the overland roughness parameters because of the direct impact of this parameter on runoff timing. It is less sensitive to the estimates of channel

roughness for the same two reasons discussed for the peak discharge.

Equivalent depth is most sensitive to the estimates of loss parameters and percent imperviousness because these parameters determine the runoff volume. Equivalent depth is most sensitive to the loss function parameter because the pervious basin area is much greater than the impervious basin area. Thus, runoff from the pervious area of the Castro Valley model will be greater than runoff from the impervious area.

5.2 Potter Valley

Potter Valley was the second basin modeled using the HEC1-ADAPT system. This basin of 92.2 square miles is much larger than Castro Valley and is mostly woodlands with some grasslands, cultivated orchards and vineyards. The model developed for Potter Valley consisted of 299 triangles. Average triangle area was about 200 acres (see Figure 20). Soil and land use data were obtained from the U.S. Soil Conservation Service and from the California Department of Water Resources respectively (31,4). Table 7 tabulates land use, soil type and CN for Potter Valley.

The modeling of Potter Valley serves to illustrate a major problem that must be addressed when using HEC1-ADAPT on larger basins. The topographic model of Potter Valley is good where existing channels are represented; however, the topographic model is not as good where channels exist, but are not modeled. Overland slopes in these unmodeled channel areas can be much less than the actual slopes. The dilemma facing the user is deciding

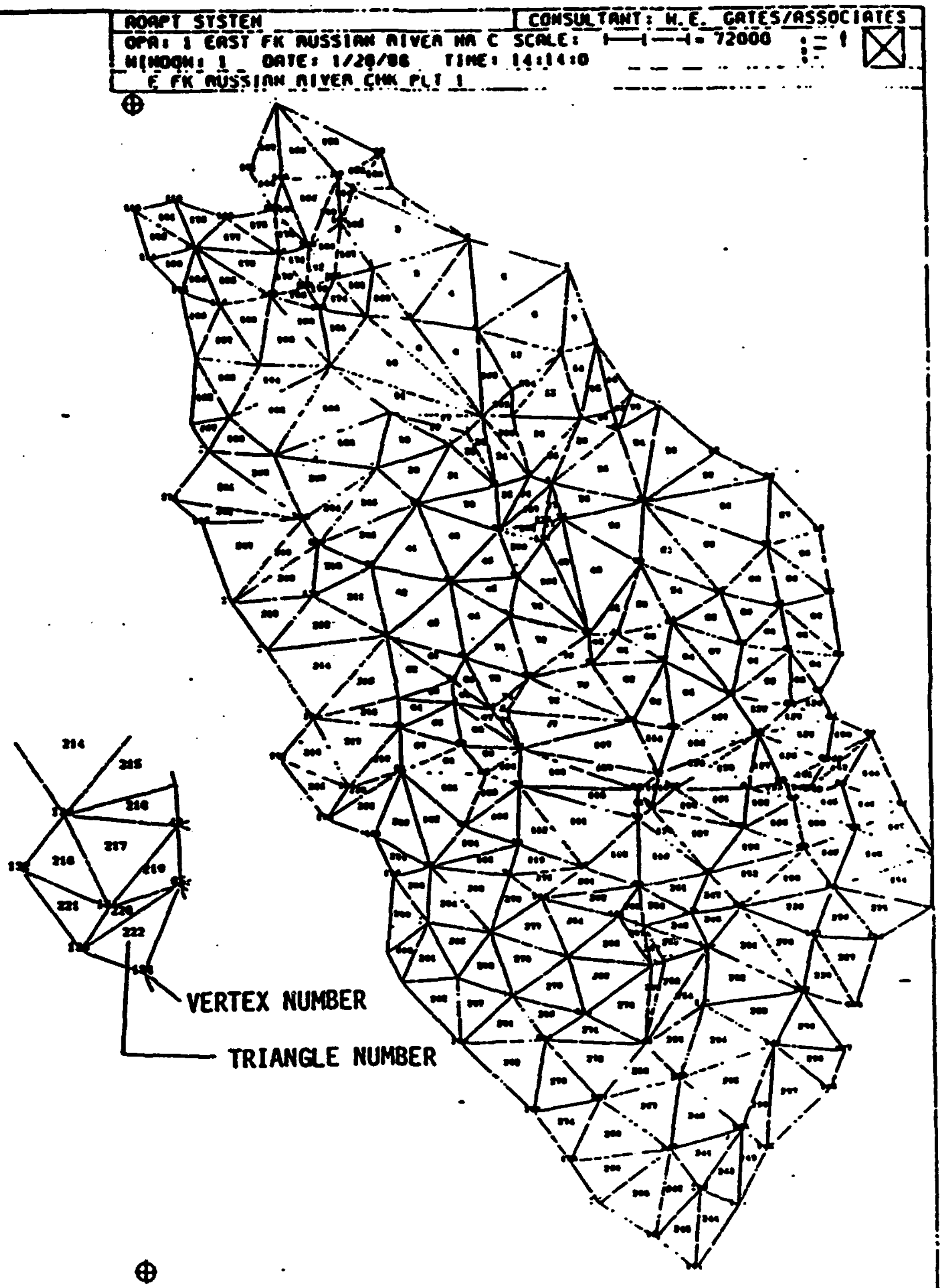


FIGURE 20 POTTER VALLEY 299-TRIANGLE TIN

TABLE 7

POTTER VALLEY LAND USE AND SOILS DATA*

LAND USE	CURVE NUMBER+ HYDROLOGIC SOIL GROUP A++	B	C	D
Chaparral		44	60	66
Grass-Oak		46	62	67
Irrigated Pasture		49	65	70
Orchard		53	67	71
Woods-Forest		55	70	77

* Source: DWR, 1972. Mendocino County Land Use Maps.
SCS, 1984. Unpublished Soil Survey Data for eastern Mendocino County.

\+ Source: SCS, 1972. National Engineering Handbook, Section 4, Hydrology.
SCS, 1975. Urban Hydrology for Small Watersheds, Tecnical Release No. 55.

++ No "A" soils are found in Potter Valley.

what resolution is necessary to give reasonable results without requiring inordinate preparation and computer time. Although the problem has not been resolved in this testing program, a possible rule of thumb for ungaged basins is to model all the streams one order less than the main stream where stream order is determined by the pattern of confluences of tributary streams and increases in the downstream direction. This will probably provide a reasonable representation of basin slopes. On gaged basins, lower resolution models can be used and calibration parameters can be adjusted to compensate.

5.2.1 Potter Valley Watershed Model

As with the Castro Valley watershed, CN losses were used to model rainfall excess in the initial runs. Since Potter Valley is a non-urban basin, Clark Unit Graph method and Muskingum channel routing were used to model the sub-basin runoff and channel flow, respectively. The HEC-1 input data for the uncalibrated Potter Valley model are on file at the HEC. Figure 21 shows the computed and observed hydrographs for the December 20, 1964 flood event generated using the uncalibrated model.

As with the Castro Valley model, the timing is quite a bit slower for the computed hydrograph. The causes of this slow response are different for the Potter Valley model however. In the Castro Valley model, the timing problems are probably a result of the inability of the present model to adequately handle man-made drainage structures. For Potter Valley, the problems appear to result from the methods used to define model coefficients.

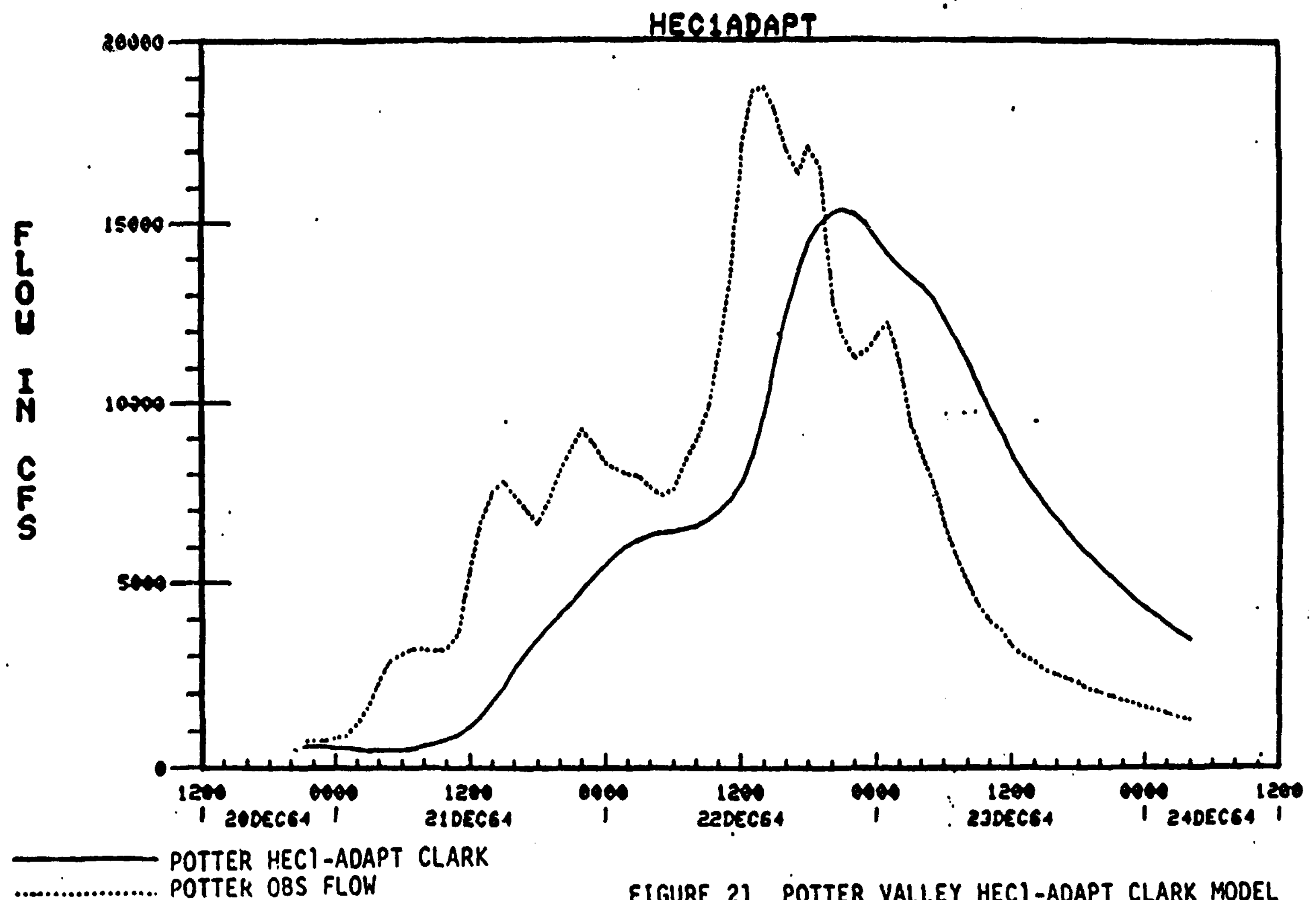


FIGURE 21 POTTER VALLEY HEC1-ADAPT CLARK MODEL
UNCALIBRATED DECEMBER 20, 1964 EVENT

As mentioned previously, the Potter Valley DTM did not capture all tributaries of the east Fork Russian River with the result that model slopes are less than actual slopes in some areas. To compound this problem, the overland flow paths derived by the model can be quite contorted. (This effect is explained in a following paragraph.) Another source of error is the way overland and channel velocities are computed. The interface program HECAD uses a simplified Manning's equation which computes velocities assuming a constant depth of flow.

The overall impact of these problems is seen in Figure 21. The computed hydrograph peaks seven hours later than the observed hydrograph and the peak is about 18 percent less than the observed. Runoff volumes are similar. Table 8 tabulates these results. Isolation of these errors to determine their individual effect on the simulation results is discussed below.

In order to gage the impact of topographic model errors on the hydrograph timing, HEC-1 input data were derived for a Kinematic Wave model using the same loss function and roughness as for the Clark model. Figure 22 shows the hydrographs computed using both models. The spikes of the Kinematic Wave hydrograph coincide quite well with the spikes in the observed hydrograph leading to the conclusion that the timing errors are mainly the result of problems with the derived Clark and Muskingum coefficients and not the result of errors in the topographic representation. Possible reasons for this are discussed below.

The interface program HECAD develops time-area curves by determining the travel time of each triangular element in the

TABLE 8

COMPARISON OF COMPUTED AND OBSERVED HYDROGRAPHS
POTTER VALLEY HEC1-ADAPT CLARK MODEL
UNCALIBRATED DECEMBER 20, 1964 EVENT

	SUM OF FLOWS (cfs-hr)	EQUIV. DEPTH (in)	MEAN FLOW (cfs)	TIME TO CENTER OF MASS (hrs)	PEAK FLOW (cfs)	TIME TO PEAK (hrs)
Computed Hydrograph	516747	8.606	6459	49.63	15320	48.00
Observed Hydrograph	539922	8.992	6749	40.51	18700	41.00
DIFFERENCE	-23175	-0.386	-290	9.12	-3380	7.00
PERCENT DIFFERENCE	-4.29	-4.29	-4.29	22.51	-18.07	17.07

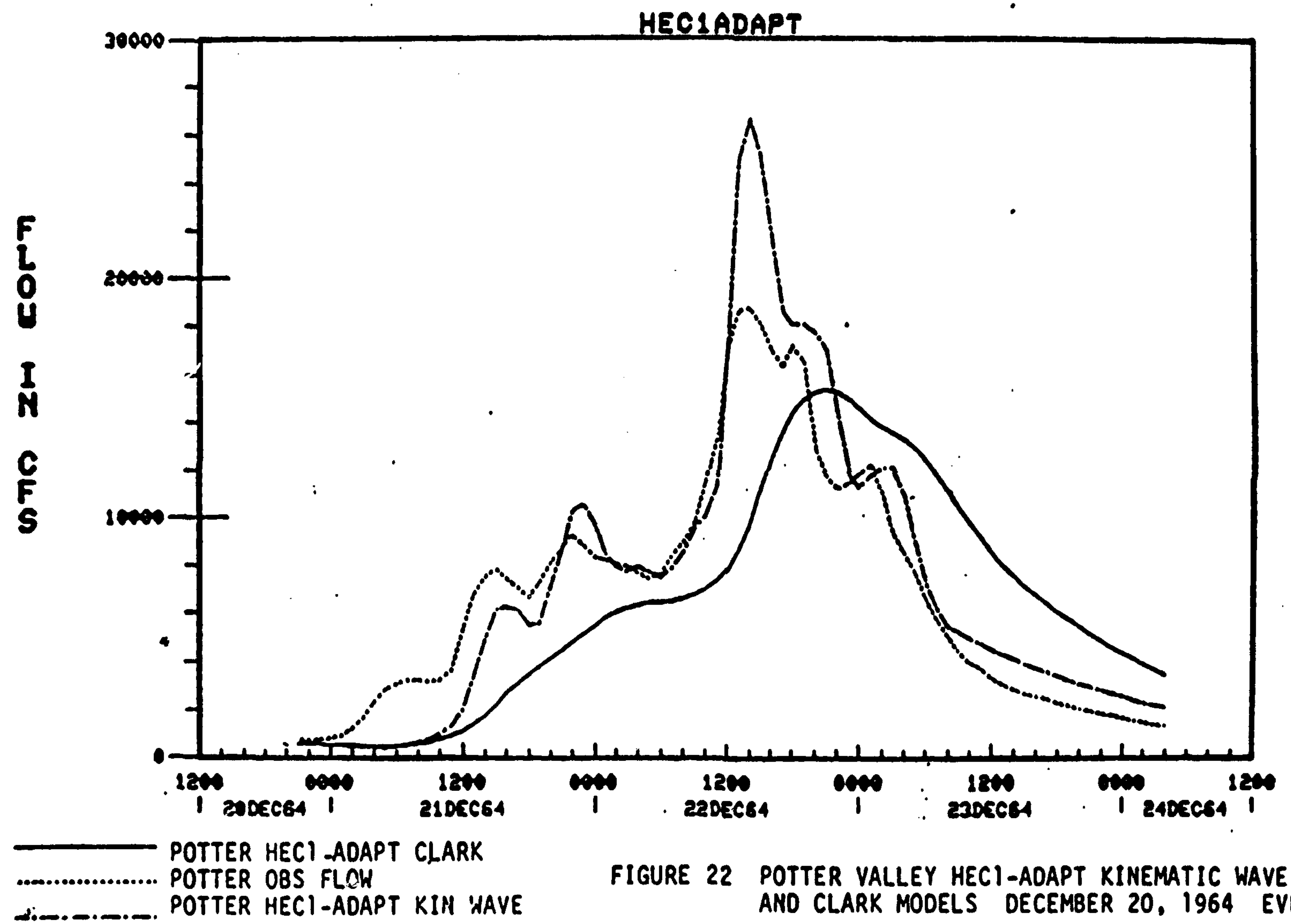
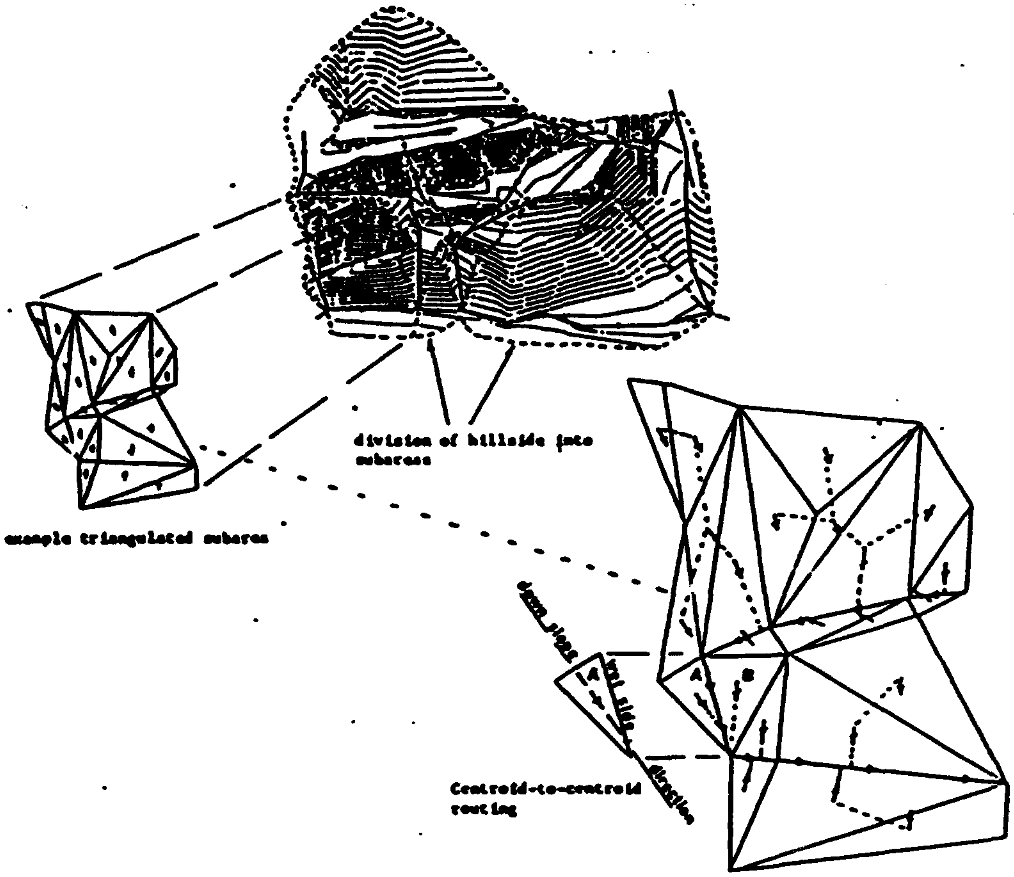


FIGURE 22 POTTER VALLEY HEC1-ADAPT KINEMATIC WAVE AND CLARK MODELS DECEMBER 20, 1964 EVENT

sub-basin to the downstream vertex of the stream link. The flow path for each triangular element is determined through a centroid-to-centroid routing technique. As mentioned previously this routing can generate flow paths that are quite contorted with some flow paths much longer than the actual flow paths (see Figure 23). This alone can cause excessively long travel times. Additionally, the overland and channel flow velocities of each triangular element are calculated using a simplified application of the Manning's equation in which constant depth is assumed. This can cause errors in the velocity computation. Since the Clark coefficients, Tc and R, and the Muskingum coefficient, K, are also derived using triangle travel times, the errors are compounded.

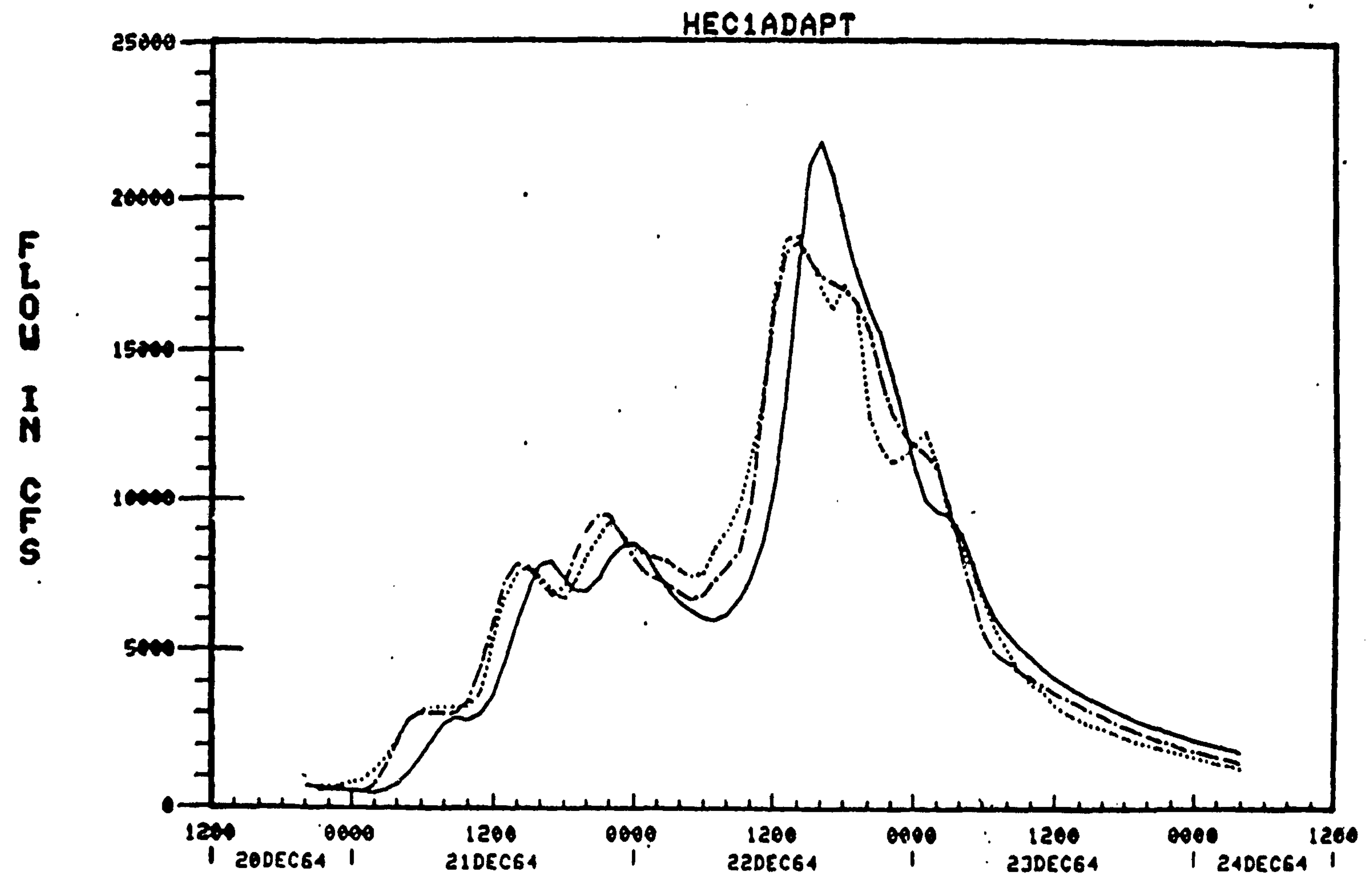
To compensate for these errors, calibration of the Clark model required the use of small roughness factors and the initial/uniform loss function. Three storm events were used. Results of this calibration are shown on Figures 24, 25 and 26. HEC-1 input data for the calibrated model are on file at the HEC. For comparison, hydrographs generated by HEC-1 using optimized Clark unit graph parameters are also shown (17). A tabulated comparison of the observed and calibrated model hydrographs for the December 20, 1964 storm appears on Table 9.

One can see from Figures 24, 25 and 26 that the HEC1-ADAPT and optimized Clark models produce hydrograph peaks, volumes and timing that are quite similar for each of these events. After completing the calibration, both models are verified using the January 14, 1974 flood event.



Source: R.N. Eli, "Runoff and Erosion Predictions Using a Surface Mine Digital Terrain Model

FIGURE 23 CENTROID-TO-CENTROID ROUTING



POTTER HEC1-ADAPT CLARK
POTTER OBS FLOW
POTTER OPT CLARK

FIGURE 24 POTTER VALLEY HEC1-ADAPT CLARK MODEL CALIBRATED (HEC-1 OPTIMIZED CLARK MODEL ALSO SHOWN) DECEMBER 20, 1964 EVENT

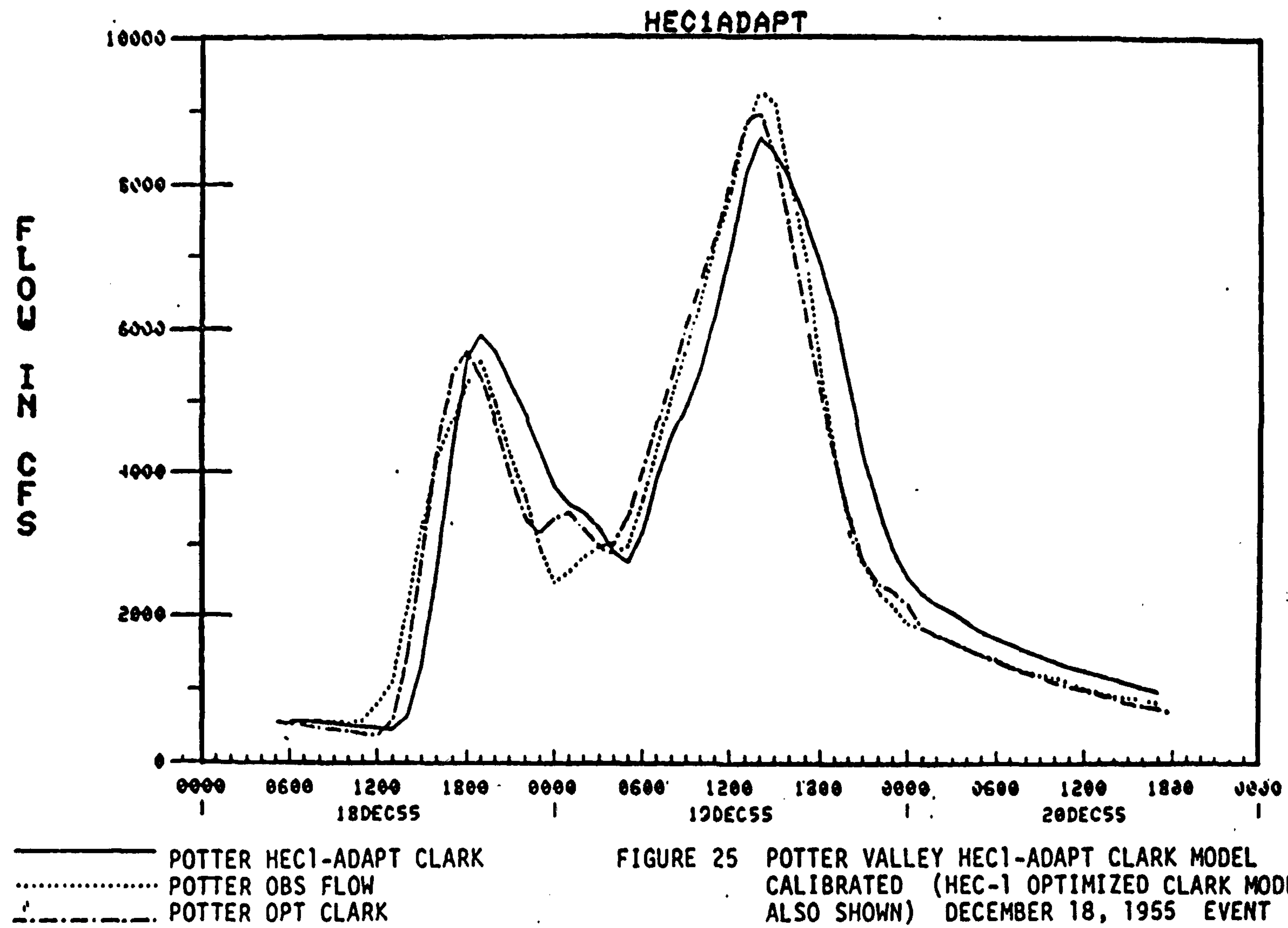


FIGURE 25 POTTER VALLEY HEC1-ADAPT CLARK MODEL CALIBRATED (HEC-1 OPTIMIZED CLARK MODEL ALSO SHOWN) DECEMBER 18, 1955 EVENT

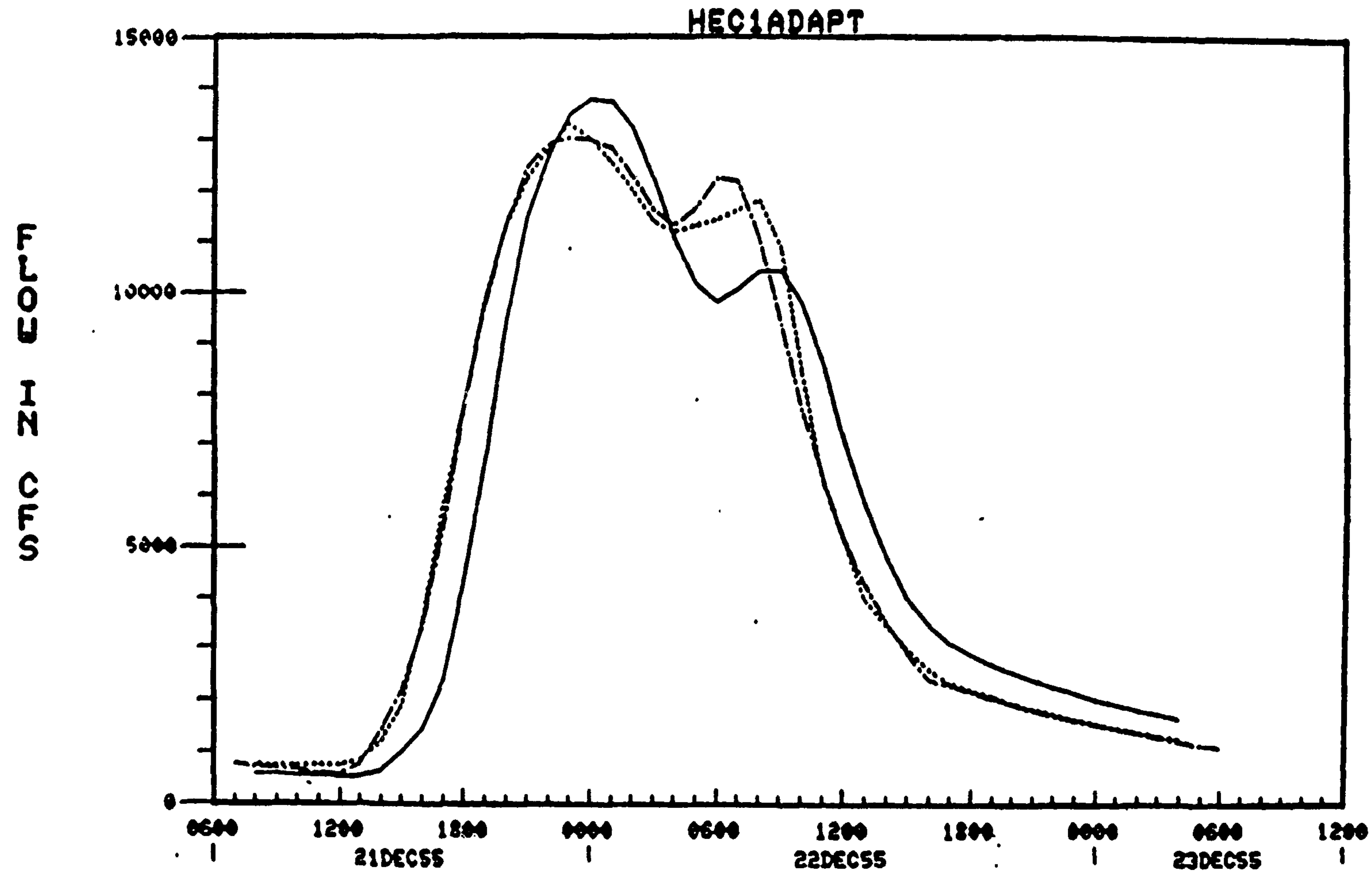


FIGURE 26 POTTER VALLEY HEC1-ADAPT CLARK MODEL CALIBRATED (HEC-1 OPTIMIZED CLARK MODEL ALSO SHOWN) DECEMBER 21, 1955 EVENT

TABLE 9

COMPARISON OF COMPUTED AND OBSERVED HYDROGRAPHS
POTTER VALLEY HEC1-ADAPT CLARK MODEL
CALIBRATED DECEMBER 20, 1964 EVENT

	SUM OF FLOWS (cfs-hr)	EQUIV. DEPTH (in)	MEAN FLOW (cfs)	TIME TO CENTER OF MASS (hrs)	PEAK FLOW (cfs)	TIME TO PEAK (hrs)
Computed Hydrograph	522499	8.702	6531	42.64	21724	43.00
Observed Hydrograph	539922	8.992	6749	40.51	18700	41.00
DIFFERENCE	-17423	-0.290	-218	2.14	3024	2.00
PERCENT DIFFERENCE	-3.23	-3.23	-3.23	5.27	16.17	4.88

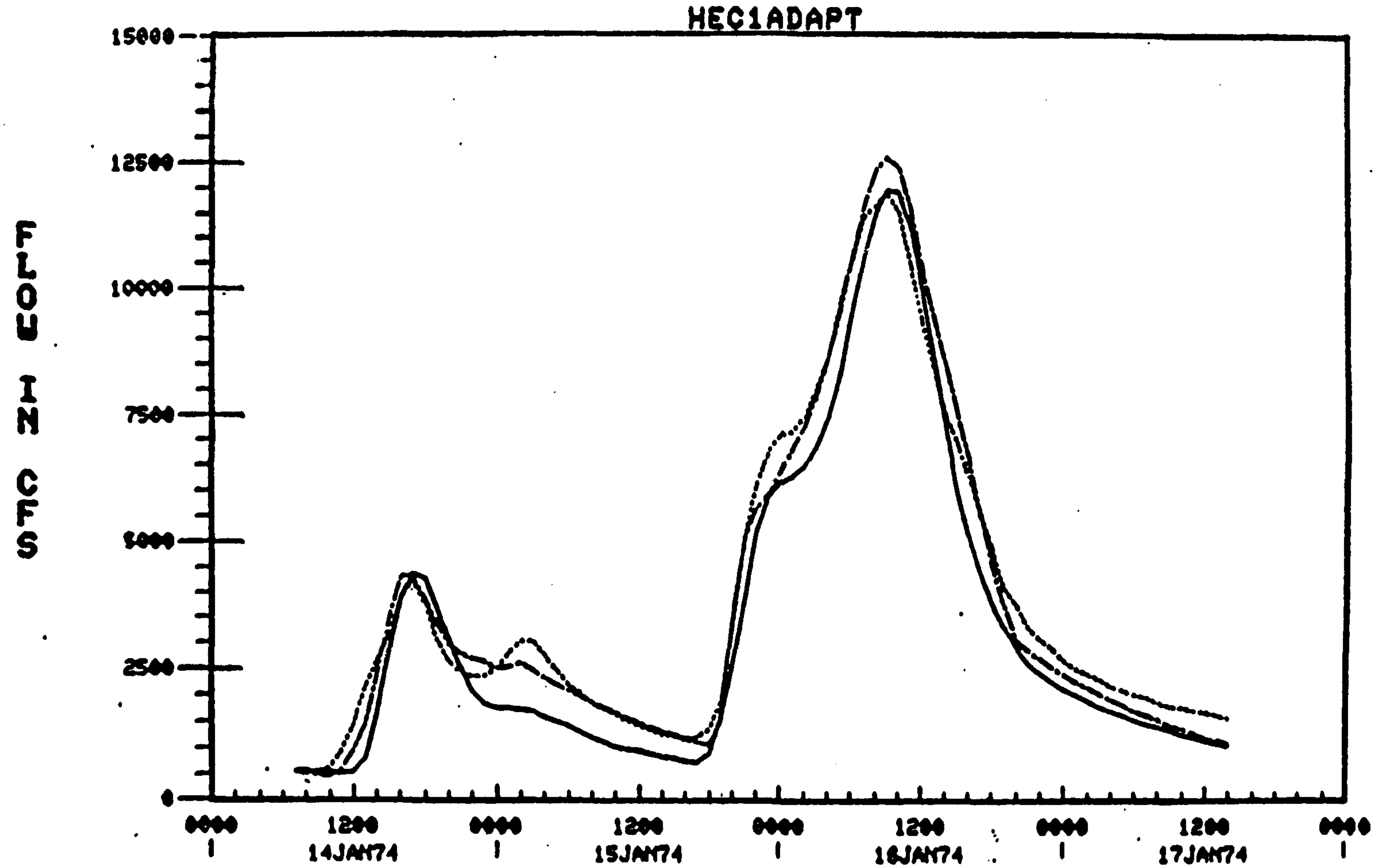
Figure 27 shows the hydrographs for these simulations while Table 10 compares the simulation results. Both the optimized Clark and HEC1-ADAPT models do a good job of reproducing this event. As with the calibration events, the two models produce hydrographs that are quite similar. From Table 10 it is seen that simulated hydrograph parameters vary by about 13 percent. As it did for Castro Valley, the HEC1-ADAPT system simulates rainfall-runoff on Potter Valley about as well as the HEC-1 optimized Clark method.

5.2.2 Sensitivity Analysis

The results of the Potter Valley sensitivity analysis are quite different from those for Castro Valley. For the Potter Valley model, peak discharge is most sensitive to overland roughness and channel roughness parameters while lag has about the same sensitivity to all calibration parameters. Equivalent depth is most sensitive to the estimates of loss parameters. Table 11 tabulates these results.

The differences in these sensitivity analyses are mainly the result of variation between the physical characteristics of the two basins. Runoff does not concentrate as rapidly in Potter Valley as it did in Castro Valley because the basin is much larger and non-urban. Consequently, the estimation of the loss function parameter becomes less significant for the peak while the overland and channel roughness parameter estimates become more significant.

Channel roughness is more significant in the Potter Valley model because the proportion of total travel time accounted for



POTTER HEC1-ADAPT CLARK
POTTER OBS FLOW
POTTER OPT CLARK

FIGURE 27 POTTER VALLEY HEC1-ADAPT CLARK MODEL VERIFICATION (HEC-1 OPTIMIZED CLARK MODEL ALSO SHOWN) JANUARY 14, 1974 EVENT

TABLE 10

COMPARISON OF POTTER VALLEY HEC1-ADAPT CLARK MODEL
AND HEC-1 OPTIMIZED CLARK MODEL HYDROGRAPHS
DECEMBER 20, 1964 EVENT

	SUM OF FLOWS (cfs-hr)	EQUIV. DEPTH (in)	MEAN FLOW (cfs)	TIME TO CENTER OF MASS (hrs)	PEAK FLOW (cfs)	TIME TO PEAK (hrs)
HEC1-ADAPT Model	264064	4.398	3301	45.07	11914	50.00
Optimized* Clark Model	302303	5.081	3779	44.53	12574	50.00
DIFFERENCE	-38239	-0.683	-478	0.54	-660	0.0
PERCENT DIFFERENCE	-12.65	-13.44+	-12.65	1.21	-5.25	0.0
OBSERVED	307073	5.161	3838	44.76	11900	50.00

* Source: HEC, 1984. Spillway Adequacy Study - Coyote Dam and Lake Mendocino.
+ Discrepancy between sum of flows and equivalent depth is caused by slight differences in drainage area between the two models.

TABLE 11

SENSITIVITY ANALYSIS
POTTER VALLEY MODEL

PARAMETER	CASE (%)	PEAK DISCH (cfs)	LAG (hrs)	EQUIV DEPTH (in)	SENSITIVITY COEFFICIENTS $\frac{\Delta Q/Q}{\Delta B/B}$*	$\frac{\Delta L/L}{\Delta B/B}$*	$\frac{\Delta D/D}{\Delta B/B}$*
Overland Roughness	Ref.	21724	42.64	8.702			
	+20	21030	42.91	8.631	0.160	0.032	0.041
	+10	21241	42.81	8.666	0.222	0.040	0.041
	-10	22217	42.52	8.742	0.227	0.028	0.046
	-20	22730	42.36	8.786	0.232	0.033	0.048
Channel Roughness	Ref.	21724	42.64	8.702			
	+20	20788	43.06	8.685	0.215	0.049	0.010
	+10	21297	42.84	8.694	0.197	0.047	0.009
	-10	21938	42.44	8.713	0.099	0.047	0.013
	-20	22690	42.23	8.721	0.222	0.048	0.011
Initial/ Uniform Loss	Ref.	21724	42.64	8.702			
	+20	20948	43.06	8.080	0.179	0.049	0.357
	+10	21337	42.84	8.388	0.178	0.047	0.361
	-10	22109	42.43	9.038	0.177	0.049	0.386
	-20	22501	42.21	9.931	0.179	0.050	0.396

* ΔQ - change in peak discharge
Q - reference value of peak discharge
ΔL - change in lag
L - reference value of lag
ΔD - change in equivalent depth
D - reference value of equivalent depth
ΔB - change in parameter (e.g. overland roughness)
B - reference value of parameter
$\frac{\Delta Q/Q}{\Delta B/B}$ - sensitivity coefficient for peak discharge

Note: reference values for state variables and parameters are from the calibrated model

by channel flow is more on larger basins than on smaller basins. Potter Valley also has fairly steep overland topography resulting in shorter overland lag times relative to the less steep channel segments.

The proportioning effect is also seen in the sensitivity of the lag. For Castro Valley, the lag was most sensitive to overland roughness, while in the Potter Valley model, lag has about the same sensitivity for both overland and channel roughness.

As with the Castro Valley, equivalent depth is most sensitive to the loss function parameter estimate which determines the volume of runoff.

5.3 Program Modifications to Improve Results

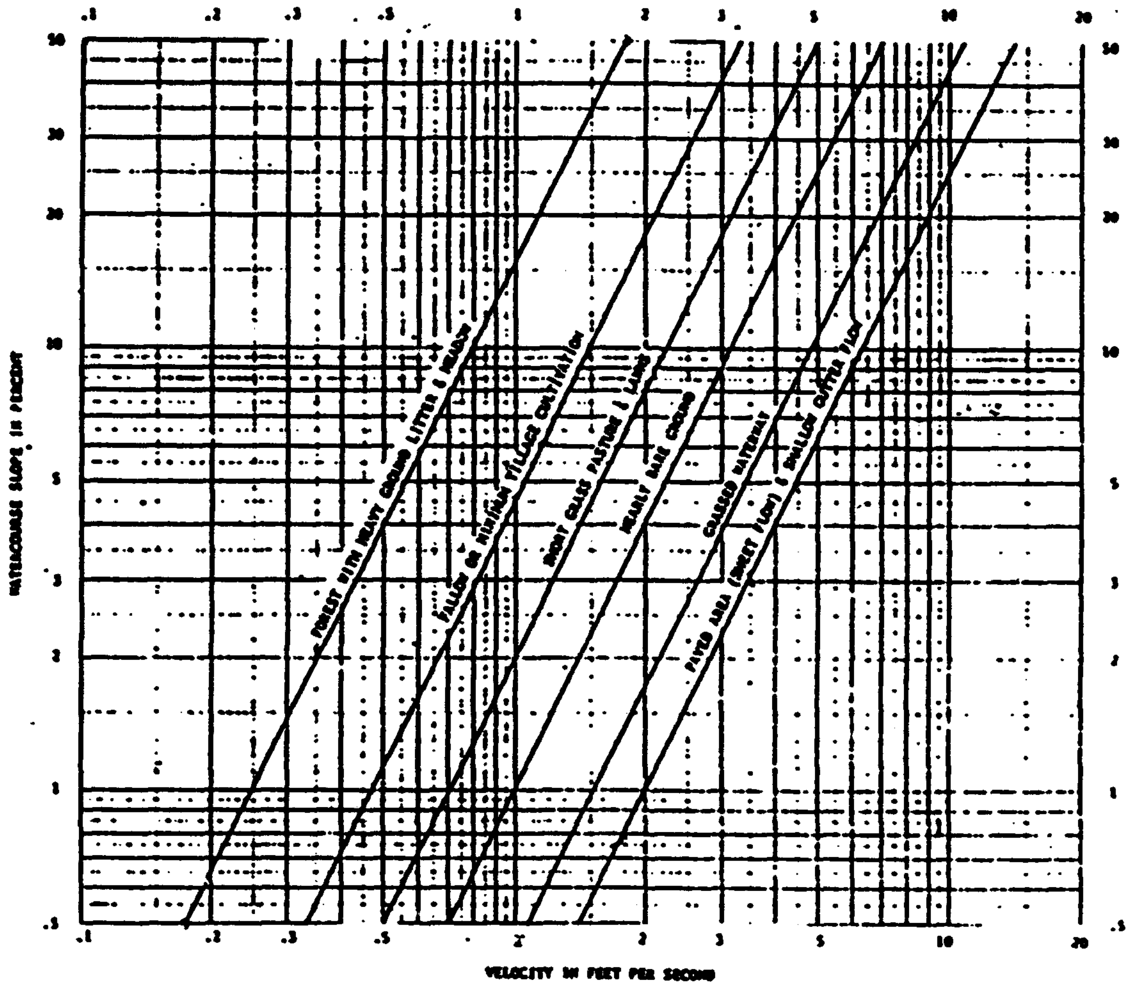
Modifications to improve the modeling of urban basins are suggested in the recommendations section of this report. A simple modification to improve the modeling of natural basins is tested and the results discussed below.

The effects of basin and channel storage are important in natural basins. In HEC1-ADAPT, the options available to model storage effects are the SCS Dimensionless Unit Graph, the Clark and the Snyder Unit Graphs and the Muskingum and normal-depth methods for channel routing. The coefficients for each of these options (except the normal-depth option) are derived through the computation of triangle travel times. The problems associated with the triangle travel time computation were discussed previously. In HECAD, the computation of overland velocities is made in one statement of the overland routing subroutine.

Modification of this subroutine was therefore simple and is discussed below.

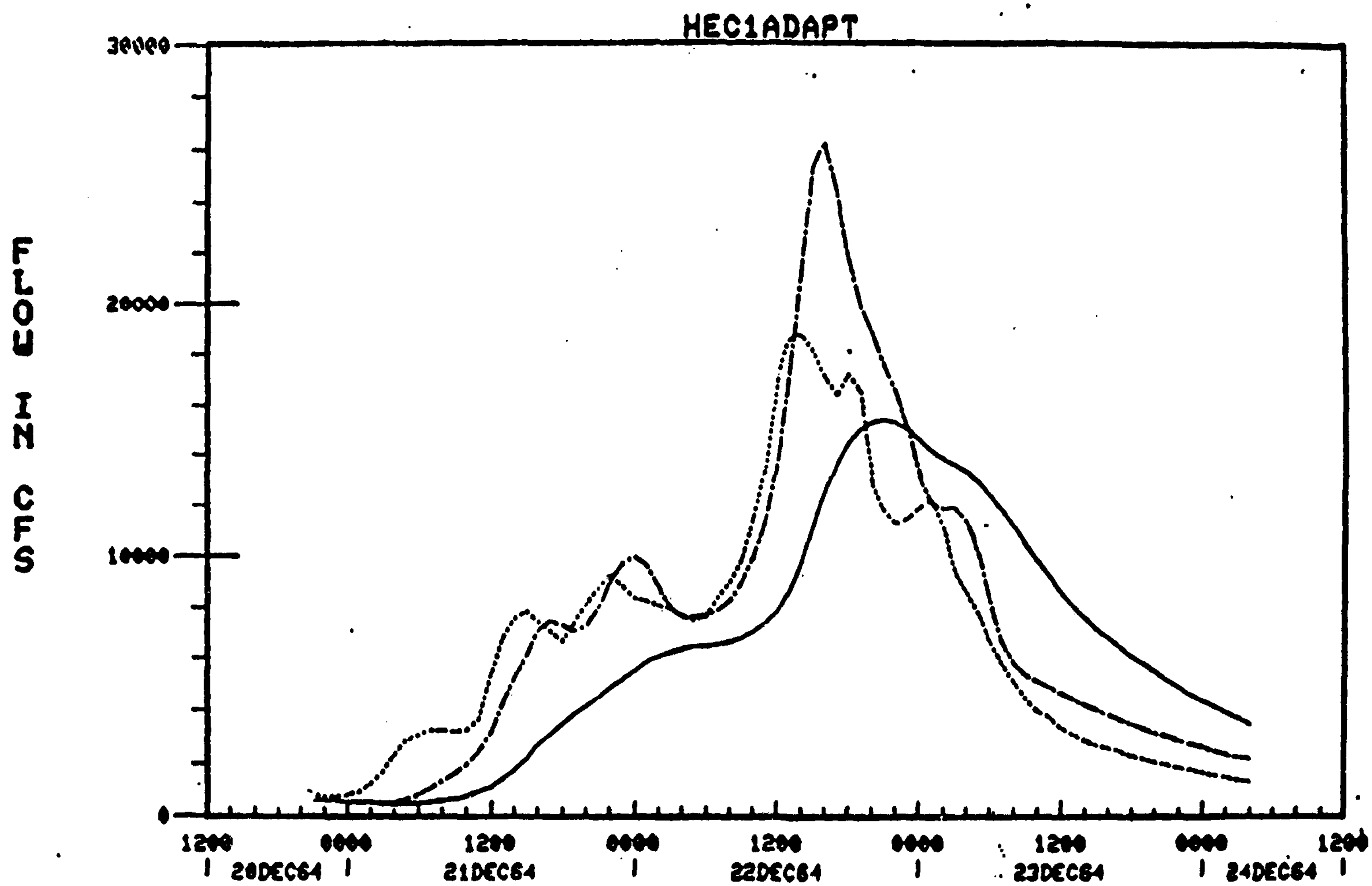
The SCS (30) has developed a chart relating land use, slope and overland velocity (see Figure 28). In a test modification, this information has been converted to equation form and incorporated into HECAD. The HEC-1 input data derived using this version of HECAD are on file at the HEC. Figure 29 shows the hydrographs generated by the uncalibrated Potter Valley model with and without the new overland velocity routine.

Hydrograph timing is much closer to the observed for the hydrograph generated using the modified routine. The quicker response has also concentrated more of the runoff volume within the 80 minute time base making both the peak discharge and equivalent depths greater than those of the previously computed hydrograph. Although the results are not conclusive, this simple modification appears to yield a significantly better response. A similar modification may be possible for the computation of stream velocities since the Muskingum coefficient K and the number of time steps are also derived using a simplified Manning's equation approach.



Source: SCS, TR-55

FIGURE 28 AVERAGE VELOCITIES FOR ESTIMATING TRAVEL TIME FOR OVERLAND FLOW



POTTER HEC1-ADAPT CLARK
POTTER OBS FLOW
POTTER HEC1-ADAPT CLARK MOD VEL

FIGURE 29 POTTER VALLEY HEC1-ADAPT CLARK MODEL
MODIFIED VELOCITY ROUTINE UNCALIBRATED
DECEMBER 20, 1964 EVENT

6. Recommendations

Two sets of recommendations are given in this section. The first suggests changes in or additions to ADAPT software which will make GIS development easier. The second suggests changes or additions to HECAD software to improve modeling results.

6.1 ADAPT Changes. The HEC1-ADAPT system consists of about forty programs and a library of utility subroutines. Of these forty, less than thirty were actually used in the testing program and many of these programs were quite small. To make software management easier, this set of programs could probably be combined into a single program. R.D. Carl, a Hydraulic Engineer in the Planning and Analysis Branch of the HEC, performed a preliminary assessment of ADAPT (3). In this assessment, he suggests that a main program be developed to connect the programs and manage the user's input and output. The management routines could contain additional error checking and data validation procedures and provide guidance to the user to help him follow the flow diagrams contained in the ADAPT documentation.

A major problem with the existing sofware is that no consistent format is used for entering data to the various programs. In his assessment, R.D. Carl also suggests incorporating a format similar to that used by other HEC programs which employ a record identifier (3). This single improvement would speed GIS development considerably.

An important part of TIN error correction is accomplished using plots of the base map, stream networks, triangle slope

directions and basin contours. A hand-made plot of the overland flow network has also been found to be quite useful for error correction. This plot is presently constructed using output from the ADAPT program LISNET. Addition of this plotting capability would speed the error correction process.

The digitizing software and hardware are very important to the development of a GIS. During this testing program, the normal digitizer setup had to be altered to enable the use of the computer program DIGITZ (which writes digitizer output into a file using the proper format) while digitizing. This hardware problem needs to be corrected. The digitizing software should be improved to make it easier to input soil and land use polygons. At present, the triangle input software is used to generate input data describing these polygons. The input formats required by the various programs are different. Consequently, output from the digitizing must be hand edited.

Development of a GIS requires assigning soil and land use to each triangle. In most cases it is much easier to handle the distribution of soil and land use types in the GIS by assigning a percentage mix to each triangle. If this is not done, the DTM must be modified to incorporate the soil and land use boundaries. This can involve considerable work redefining triangles and making sure that the topographical representation remains intact. The present model allows assignment of a mix of land uses to individual triangles through the program LUIN. This same capability needs to be developed for inserting mixes of soil

types by triangle.

6.2 HECAD Changes. Given an established GIS, there are many ways to derive input for hydrologic modeling. In HEC1-ADAPT for example, CN's are derived from associations of land use and soil type in each triangle. Clark coefficients are derived using triangle slopes, roughnesses and slope directions. Alternate methods for computing these coefficients, like those described by Eli (6,7) and Li (25), are available and could be incorporated into the existing program to take better advantage of the capabilities of the GIS.

Eli has developed a methodology that computes routing coefficients using the overland flow paths defined by triangle slopes (6). Incorporation of this method or a similar method would probably improve the derivation of Clark, Snyder, SCS and Muskingum coefficients.

An alternate method of computing overland velocities was examined earlier in this report. The preliminary testing suggested that this method may be better than the one presently employed.

Only two methods to compute infiltration are available in the present model. It would be fairly easy to add a Holtan method option. Additional data required by this method could be stored in the Soil Matrix File. An additional HECAD routine would have to be developed to derive the Holtan parameters and output the HEC-1 input data file.

An improvement in the modeling of urban basins would probably be accomplished if all the flow elements allowed in the

HEC-1 Kinematic Wave option were utilized, ie: two overland flow elements and three channel elements. The additional information required could be stored in the triangle file. Overland flow elements could model runoff from different land uses in each sub-basin. Channel elements could model the local drainage systems, interceptors and main channels. The present model allows only one overland flow plane and one main channel.

7. Summary and Conclusions

7.1 Model Resolution. Although only limited testing was done on the effect of model resolution, the results appear to confirm those of earlier researchers (8). Higher resolution models capture more of the existing terrain features including the smaller tributary streams and valleys and provide a more accurate topographic representation. The result of this increased resolution is a quicker runoff response and a greater peak discharge on the basins tested.

As stated in the Potter Valley section of this report, a major difficulty for the user is deciding what model resolution is appropriate for the purposes of a given study. The simple rule of thumb proposed in this report will probably be more than adequate for rainfall-runoff modeling on larger basins. Restated, the rule is to model all streams one order less than the main stream where stream order increases in the downstream direction. Additional experience with this technique will be necessary before a more definitive solution is found.

7.2 Modeling Ungaged Basins. The uncalibrated Castro Valley and Potter Valley models produced hydrographs that were quite similar to the historical events. In both situations the predicted volumes were within about six percent of observed volumes. Peak discharges were under-predicted about six percent in the Castro Valley model and by about 18 percent in the Potter Valley model. In both models, the lag times were over 20 percent greater for the predicted hydrographs than for the observed

hydrographs. This disparity in lag time is the major difference between computed and observed hydrographs in both simulations.

In the Castro Valley model, the timing problems are probably due to the inability of the model to account for the effect of man-made drainage structures on the runoff response. This is compensated for in the calibration by using low overland and channel roughness factors and by using the initial/uniform loss function to get more volume on the rising side of the hydrograph. In the Potter Valley model, the long lag is probably due to problems with the way Clark and Muskingum coefficients and the time-area curves are derived. As with the Castro Valley model, modified roughness factors and the initial/uniform loss function are used to obtain a calibration.

Even with these problems the simulation results are reasonable for ungaged basins. This is very encouraging because all input data for the runoff model is derived directly from non-calibrated GIS's of the drainage basins. There appears to be great potential for GIS's to provide a basis for modeling ungaged basins.

7.3 Modeling Urban and Non-Urban Basins. The flexibility of the system is demonstrated by the relative success in reproducing hydrographs for both an urban basin and a non-urban basin. Although some problems remain, in general the methodology used to develop coefficients for the rainfall-runoff model appears to be sound.

In conclusion, the HEC1-ADAPT system accounts for the

hydrologic diversity of a drainage basin and accomodates the derivation of runoff model coefficients. Since this derivation is based on a physical representation of the basin, HEC1-ADAPT provides a reasonable method for simulating the response of ungaged watersheds. The methodologies used to develop both the GIS and the input data for the rainfall-runoff model are fairly sound. Preliminary analysis and experience with the model indicate that simple modifications to both ADAPT and to the interface HECAD could be implemented and would improve the model results.

8. REFERENCES

1. Charbonneau, R., J.P. Fortin and G. Morin, 1975. The Cequeau Model. Descriptions and Examples of its Use in Problems Related to Water Resources Management. Intitut Nationale de la Recherche Scientifique. Universite du Quebec.

2. Davis, D.W., 1978. "Comprehensive Flood Plane Studies using Spatial Data Management Techniques." Water Resources Bulletin. AWRA. Vol. 14, No. 3, pp. 587-604.

3. Carl, R.D., 1985. "ADAPT Software Package." Internal Memorandum. The Hydrologic Engineering Center, Davis, California.

4. DWR, 1972. "Land Use Maps, Mendocino County." The Resources Agency, Department of Water Resources, Central District, Sacremento, California.

5. Eli, R.N., B.L. Palmer and R.L. Hamrio, 1980. "Digital Terrain Modeling Applications in Surface Mining Hydrology." Symposium on Surface Mining Hydrology, Sedimentology and Reclamation, pp. 445-453. University of Kentucky, Lexington, Kentucky.

6. Eli, R.N. and M.J. Paulin, 1981. "Runoff and Erosion Predictions using a Surface Mine Digital Terrain Model." Symposium on Surface Mining Hydrology, Sedimentology and Reclamation, pp. 201-210. University of Kentucky, Lexington, Kentucky.

7. Eli, R.N., 1981. "Small Watershed Modeling using DTM." Water Forum '81. ASCE Specialty Conference, Sheraton Palace Hotel, San Fransisco, California, August 10-14, Vol. 2.

8. Eli, R.N. and M.J. Paulin, 1983. Improving Watershed Model Accuracy by Using Digital Topography. Water Research Institute, West Virginia University, Morgantown, West Virginia.

9. Eli, R.N., 1983. "Geographic Information Systems in Coal Mine Applications." First Conference on Use of Computers in the Coal Industry, August 1-3, West Virginia University, Morgantown, West Virginia.

10. Fabos, J.G. and S.A. Joyner,Jr., 1976. A Landscape Planning Model as an Aid to Decision Making for Community Growth and Management. Massachusetts Agrcultural Experiment Station, University of Massachusetts at Amherst, Paper No. 2013.

11. Grayman, W.M. et al., 1975. "Land-Based Modeling System for Water Quality Management Studies." Journal of the Hydraulics Division, ASCE, Vol. 101, No. HY5, Proc. Paper 11327, pp.567-580.

12. Grayman, W.M., R.M. Males and J.J. Harris, 1982. "Use of Integrated Spatial Data and Modeling Capabilities for Urban Runoff Analysis." International Symposiun on Urban Hydrology, Hydraulics and Sediment Control, pp. 249-256, University of Kentucky, Lexington, Kentucky.

13. Gupta, S.K. and S.I. Soloman, 1977. "Distributed Numerical Model for Estimating Runoff and Sediment Discharge of Ungaged Rivers." Water Resources Research. Vol. 13, No. 3, pp. 613-636.

14. HEC, 1975. "Phase I Oconee Basin Pilot Study, Trail Creek Test. An Investigation of Concepts and Methods for Broadened Scope Flood Plain Information Studies." The Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California.

15. HEC, 1977. "Proceedings of a Seminar on Variable Grid Resolution Issues and Requirements." The Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California.

16. HEC, 1983. "Applications of Spatial Data Management Techniques to HEC-1 Rainfall-Runoff Studies." Training Document Number 19. The Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California.

17. HEC, 1984. "Spillway Adequacy Study-Coyote Dam and Lake Mendocino, California." Special Projects Memo No. 84-9. The Hydrologic Engineering Center, U.S.Army Corps of Engineers, Davis, California.

18. HEC, 1985. "Flood Hydrograph Package, HEC-1." The Hydrologic Engineering Center, CPD No. 1, U.S. Army Corps of Engineers, Davis, California.

19. HEC, undated. "Oconee Style Hydrology Workshop." Urban Hydrology Course Workshop for Castro Valley. The Hydrologic Engineering Center, U.S. Army Corps of Engineers, Davis, California.

20. Heggen. R.J., 1983. Runoff Model for Watersheds of Nonhomogenous Hydrologic Characteristics. Technical Report 176, New Mexico Water Resources Institute, Las Cruces, New Mexico.

21. Hong, H.M. and R.M. Eli, 1985. "Accumulation of Streamflow in Complex Topography." Computer Applications in Water Resources. ASCE Conference, Hyatt Regency Hotel, Buffalo, New York, June 10-12.

22. Huggins, L.F. et al., 1973. Simulation of the Hydrology of Ungaged Watersheds. Technical Report 38. Indiana Water Resources Research Center, Purdue University, West Lafayette, Indiana.

23. Jett, S.C., A.D. Weeks and W.M. Grayman, 1979. "Geographic Information Systems in Hydrologic Modeling." Proceedings of the Hydrologic Transport Smyposium, pp.127-137. American Society of Agricultural Engineers, St. Joseph, Michigan.

24. LaGarde, V.E., 1982. Computer-Aided Watershed Analysis. Miscellaneous Paper EL-82-2. Environmental Laboratory, U.S. Army Engineers Waterways Experiment Station, Vicksburg, Mississippi.

25. Li, E.A., et al., 1975. "Generating Rainfall Excess Based on Readily Determinable Soil and Landuse Characteristics." Transactions, American Society of Agricultural Engineers, Vol. 20, No. 6, pp. 1070-1078.

26. McKim, H.L et al., 1984. Integration of Landsat land cover data into the Saginaw River Basin geographic information system for hydrologic modeling. Special Report 84-1, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

27. Orlob, G.T., 1983. Mathematical Modeling of Water Quality Streams, Lakes and Reservoirs. New York: John Wiley and Sons.

28. Pentland, R.L. and D.R. Cuthbert, 1974. "Operational Hydrology for Ungaged Streams by the Grid Square Technique." Water Resources Research, Vol.7, No. 2, pp. 283-291.

29. SCS, 1972. "National Engineering Handbook, Section 4, Hydrology." USDA, Soil Conservation Service.

30. SCS, 1975. "Urban Hydrology for Small Watersheds." Technical Release Number 55. USDA, Soil Conservation Service Engineering Division.

31. SCS, 1984. Unpublished Soil Survey Data, Eastern Mendocino County, California. USDA, Soil Conservation Service, Ukiah, California.

32. Seader, D. and S. Grava, 1971. "A Demonstration of the use of Computer-Aided Land-Use Modeling for Regional Service System Design." Proceedings of the 6th Annual Urban Symposium, Fairfax, Virginia.

33. Thomsen, A.G. and W.D. Striffler, 1980. A Watershed Information System. Completion Report 100. Colorado Water Resources Research Institute, Colorado State University, Fort Collins, Colorado.

34. W.E. Gates and Associates, Inc., undated. "ADAPT Documentation." W.E. Gates and Associates, Inc., 1515 Cincinnati-Batavia Pike, Batavia, Ohio, 45103.

APPENDIX A

Modifications and/or Corrections to ADAPT System Routines

The first two tasks of the testing program were to determine whether the necessary hardware and software to develop a data base were available and whether everything was working properly. It was felt that this could be best accomplished by building a GIS from scratch. A small urban basin, Castro Valley, was chosen for this purpose. Castro Valley has been used in a number of other studies by the HEC.

The first Castro Valley model was constructed by following Figure 1 in Section 2, Volume 1 of the HEC1-ADAPT documentation. Program errors and problems were corrected as they were encountered. Some bugs may remain in the HEC1-ADAPT programs that were not used in this test application.

The HEC1-ADAPT programs were compiled and linked by R.D. Carl at the HEC in January, 1985. One additional program, DIGITZ, was compiled and linked in July, 1985. The DIGITZ program provides a systematic method for inserting triangles using the HEC digitizer. A short description of this program and the other programs used in the testing program is given in Table 1.

As mentioned previously, program errors and problems were corrected as required during the process of building a GIS for the Castro Valley. Table 2 lists these program changes. A hard copy of the source code of each of these programs is on file at the HEC with the required changes to the original code indicated.

After completing the above tasks it was necessary to check the computation routines within the interface program HECAD. Much of this work involved inserting write statements into various subroutines of the interface to print out intermediate and final results. These results were then verified by hand computations. An error in the overland travel time computation was discovered and corrected in this step.

Other subroutines were checked by comparing HECAD output with information contained in the data base and listed for this purpose. The HECAD-derived initial/uniform loss coefficients and curve numbers were checked this way. Table 3 gives a list of the HECAD routines that were checked and modified. The modifications are described in Table 2.

Miscellaneous Quirks and Errors

The following section describes other problems or possible errors in logic that were encountered while developing the GIS for this testing program.

1. There is a problem with simulating small events in which the initial abstraction is greater than total rainfall on some sub-basins. HEC-1 will not run when initial abstraction is greater than total rainfall. Thus, HEC-1 will abort upon encountering a sub-basin with less rainfall than initial abstraction. With the existing setup, flow cannot be routed through a non-rainfall-excess producing basin.

2. The horizontal distance rather than slope distance is used for computing travel times for the Clark, SCS, and Snyder

methods. This will produce errors if steep ground slopes exist in the basin being studied.

3. HECAD does not make use of the land use information that is established in the triangle file using the programs POLDIG, POLYCR, and UNPIN. The data inserted using these programs can be accessed by PENPLT to make Unique Attribute Polygon (UAP) and Single Attribute Polygon (SAP) plots, but it is still necessary to run program LUIN to insert the land use data required to run HECAD.

POLDIG, POLYCR and UNPIN can also be bypassed for insertion of soils data. Programs ADSOIL, which establishes the percent of each hydrologic group associated with each soil type, and TRIIN1, which can be used to insert a soil number into a given column of the triangle file, can be run to write this information into the proper files.

Programs POLYCR, POLDIG and UNPIN need to be run only when UAP or SAP plots are desired.

4. In the triangle file, HECAD requires land use data in Columns 30 through 33 and a soil number in Column 49 in order to execute. The programs described in Item 3 above are used to establish this data. Additionally, HECAD requires the Manning's roughness for each stream link. Program NETIN is used to input the roughness into Column 33 of the network file. None of these requirements are mentioned in the HEC1-ADAPT documentation.

5. There appear to be some problems with the curve number adjustment algorithm. For antecedent precipitation values lower than about 0.9 inch, the adjusted curve number is actually lower

than the unadjusted value for the dormant season. This doesn't seem to make sense. Otherwise, the algorithm appears to give reasonable values.

6. The time-step size chosen for the computation interval should be a function of the stream link with minimum travel time. If the computation interval is larger than the time it takes for water to traverse the length of the stream link, then some error will be introduced into the routing computations.

Time Required to Develop a GIS

The time required to develop a GIS is of course a function of the size and complexity of the drainage basin. To provide some idea of this time requirement, a time log was kept during the development of the Castro Valley 82-triangle model. Table 4 shows this time log.

This particular data base took approximately one week to develop. However, a major requirement not included in this log is the time to get "up to speed" with the technology. The first Castro Valley model provided a simple data base for learning the structure and procedures of the method. Thus, the one-week period to build the 82-triangle model assumes prior experience with HEC1-ADAPT.

Documentation

Table 5 tabulates the HEC1-ADAPT programs used in the testing program, the source and executable file names and the input and output files required to run them for the 82-triangle Castro Valley model.

The computer code sheets that were used to run the programs are also on file at the HEC.

TABLE 1

PROGRAM DESCRIPTIONS

PROGRAM	DESCRIPTION
DIGITZ	Provides a systematic way of inputting triangle data using the HEC DATATB II digitizer.
DIGIT	Prepares a triangle data file from the digitizer data file for input to FILEST.
FILEST	Converts output of DIGIT to input for VERTEX and CRETRI.
VERTEX	Establishes vertex file using input generated by FILEST or manually.
CRETRI	Establishes triangle file and adds topology data to vertex file.
PENPLT	Produces display plots of GIS at any scale. Also used for error checking.
FIXVER	Corrects or modifies topology in data base by deletion, redefinition or addition of vertices.
FIXTRI	Corrects or modifies topology in data base by deletion, redefinition or addition of triangles.
BOUNV	Establishes boundary file which is input for EDITNT and OVERLN programs. Also used to identify topologic hole problems.
ADJCHK	Identifies adjacency and topologic errors in the data base.
CRNET	Establishes stream network and stream drainage file.
EDITNT	Corrects topologic errors in stream file. Also identifies topographic errors in data base.
OVERLN	Establishes overland drainage network and stores results in stream network file.
LISNET	Produces a listing of the values of selected data types stored within the stream network file.
VLIST	Produces a listing of the vertex file.
TLIST	Produces a listing of the triangle file.
POLDIG	Inserts UAP numbers or SAP values in a specified column of the triangle file using digitizer coordinates.
UNPIN	Assigns attribute values to triangles based on the UAP numbers they have been assigned.
POLYCR	Allows manual definition of a vertex chain for insertion of SAP or UAP values. Can also be used for coorecting POLDIG errors.
INTSMF	Initializes the soil matrix file.
ADSOIL	Used to modify soil charateristic values in the soil matrix file.

TABLE 1 (Cont.)

PROGRAM	DESCRIPTION
LUIN	Used to insert the percentage mix of land uses in each triangle into the triangle file.
TRIIN1	Used to change or insert a number or value in a specified column of the triangle file (e.g. used to insert soil number in col. 49 in this testing program).
NETIN	Used to insert stream link attribute values into the stream network file (e.g. used to insert Manning's roughness for each stream link into col. 33 in this testing program).
SEGINS	Used to insert sub-watershed identifiers for each stream link into the stream network file.
HECAD	Interface program which connects ADAPT and HEC-1.
HEC-1	The HEC rainfall-runoff program.

TABLE 2

PROGRAM MODIFICATIONS

PROGRAM	MODIFICATION
DIGIT	Modified the call statement "CALL STATNE". STATNE is a subroutine in the library of subroutines which computes easting and northing based on a given latitude, longitude and zone. The call statement specified the wrong variable name for zone.
PUTL	Modified a read statement in PUTL. PUTL is a library subroutine that is called during the execution of CRENET. CRENET was aborting on an "end-of-file" error. Inserted an "End= " into the read statement.
POLDIG	Modified two read statements to allow use of the digitizer program DIGITZ for insertion of polygon data.
PENPLT	Modified a write statement in subprogram CONTOR. The original subprogram specified the wrong logical file number.
OVERLN NETIN SEGINS	Added a common block to each of these programs. The library subroutine GETL is called during the execution of each program and requires the variables in the common block.
HECAD	Changed a variable name in subroutine OLAND to correct an error in the travel time computation. Modified OLAND and CHANK subroutines to get proper insertion of the KO card in the HEC-1 data file for the kinematic wave option. Modified OLAND to compute cumulative time-area curve coordinates. Original subroutine computed incremental ordinates. This resulted in HEC-1 computing negative unit hydrograph ordinates. Modified OLAND to do interpolation on cumulative time-area curve ordinates to obtain a smoother function. Modified OLAND to correct travel time vs. stream length histogram. Original computation left out the first two links in the non-kinematic wave runs. Modified rain gage weight computation routines in subroutine RAINW. Original routine did not work. Modified subroutine OLAND to get baseflow cards for Clark, Snyder and SCS methods. Original routine inserted only baseflow cards for the kinematic wave option.

TABLE 3

HECAD PROGRAM CHECKS

HECAD COMPUTATIONS	CHECKED	MODIFIED
Rain gage weighting		
temporal	*	*
areal	*	* (new routine)
Loss parameters		
initial/uniform	*	
curve numbers	*	
Curve number adjustment	*	
Percent imperviousness	*	
Overland flow parameters		
Clark	*	* (time-area curve)
Snyder	*	* (time-area curve)
SCS	*	* (time-area curve)
Kinematic wave	*	* (insertion of KO card)
Channel routing parameters		
Muskingum	*	
Kinematic wave	*	
Baseflow parameters	*	* (insertion of baseflow cards for Clark, Snyder and SCS)

Note: uniform flow, reservoir routing and channel loss computations were not checked.

TABLE 4

CHRONOLOGY OF THE 82-TRIANGLE
CASTRO VALLEY MODEL CONSTRUCTION

DATE	TIME	COMMENT
September 20, 1985	9:00-16:30	Create and digitize TIN.
September 23, 1985	9:30	DIGIT
" " "	10:30	FILEST
" " "	11:00-11:30	VERTEX
" " "	14:00	CRETRI
" " "	15:00	PENPLT
" " "	16:00-16:30	FIXVER
September 24, 1985	8:00	PENPLT
" " "	10:00	BOUNV
" " "	10:15	ADJCHK
" " "	10:30	CRNET
" " "	11:00	OVERLN
" " "	11:30-12:30	LISNET
September 25, 1985	12:00-16:30	TIN modification. Use DIGIT to determine coordinates of new triangles.
September 26, 1986	8:00	FIXVER
" " "	9:00	FIXTRI
" " "	10:00-12:00	BOUNV, ADJCHK, CRNET, OVERLN, LISNET
" " "	14:00-15:30	PENPLT
" " "	15:30-17:00	POLDIG input preparation
September 27, 1985	9:00-11:00	POLDIG
" " "	15:30-16:30	POLYCR
September 30, 1985	9:00-10:00	PENPLT
" " "	10:30-11:30	UNPIN, PENPLT
" " "	15:00-16:30	INTSMF, ADSOIL, LUIN
" " "	16:30-17:00	TRIIN1
October 1, 1985	8:00-10:00	NETIN
" " "	13:00-13:30	SEGINS
" " "	13:30-14:00	HECAD
" " "	14:00-15:00	HEC-1

Total	about 36 hours	

TABLE 5

ADAPT PROGRAMS USED TO DEVELOP 82-TRIANGLE CASTRO VALLEY MODEL

PROGRAM	SOURCE	EXECUTABLE	DATA	JOBSTREAM
DIGIT	DIGIT.S	DIGIT.X	i : header cards TAPE20 (digitizer deck) o : DIGIT.2 OUTDIG (printer output)	DIGIT.J
FILEST	FILEST.S	FILEST.X	i : DIGIT.2 FILEST.2 o : FLT.2 FLV.2 FLP.2 FILEOUT (printer output)	FLEST.J
VERTEX	VERTEX.S	VERTEX.X	i : VRTEX.2 FLV.2 FLP.2A (FLP.2 plus header card) o : CSTRO.V1 VERTOUT (printer output)	VRTEX.J
CRETRI	CRETRI.S	CRETRI.X	i : FLT.2A o : CSTRO.T1 CSTRO.V1 CRTOUT (printer output)	CRTRI.J
PENPLT	PENPLT.S	PENPLT.X	i : PEN.1 CSTRO.V1 CSTRO.T1 o : PLT.P PENOUT (printer output)	PEN.J
FIXVER	FIXVER.S	FIXVER.X	i : FXVR.2 o : CSTRO.V1 CSTRO.T1 FXVROUT (printer)	FXVR.J

Note: i - input file
o - output file

TABLE 5 (cont.)

PROGRAM	SOURCE	EXECUTABLE	DATA	JOBSTREAM
BOUNV	BOUNV.S	BOUNV.X	i : CSTRO.T1 o : CSTRO.B1 BOUNOUT (printer)	BOUNV.J
ADJCHK	ADJCHK.S	ADJCHK.X	i : CSTRO.T1 CSTRO.V1 o : ACHKOUT (printer)	AJCHK.J
CRNET	CRNET.S	CRNET.X	i : CSTRO.T1 CSTRO.V1 o : CSTRO.N1 CRNTOUT (printer)	CRNET.J
LISNET	LISNET.S	LISNET.X	i : LSNT.1A LSNT.2A CSTRO.N1 CSTRO.T1 o : LSNTOUT (printer)	LSNT.J
OVERLN	OVERLN.S	OVERLN.X	i : CSTRO.B1 CSTRO.V1 CSTRO.T1 o : CSTRO.N1 OVROUT (printer)	OVR.J
DIGIT Note: used second time to determine coordinates of new triangles added to data base	DIGIT.S	DIGIT.X	i : header cards TAPE20 o : DIGIT.3 OUTDIG (printer)	DIGIT.J
FIXVER	FIXVER.S	FIXVER.X	i : FXVR.3 o : CSTRO.V1 CSTRO.T1 FXVROUT (printer)	FXVR.J
FIXTRI	FIXTRI.S	FIXTRI.X	i : FXTR.2 o : CSTRO.V1 CSTRO.T1 FXTROUT (printer)	FXTR.J
BOUNV	*			
ADJCHK	*			
CRNET	same as before			
OVERLN	*			
LISNET	*			

TABLE 5 (cont.)

PROGRAM	SOURCE	EXECUTABLE	DATA	JOBSTREAM
POLDIG	POLDIG.S	POLDIG.X	i : header card TAPE20 CSTRO.V1 CSTRO.T1 o : PLDG.2A PLDGOUT (printer)	PLDG.J
POLYCR	POLYCR.S	POLYCR.X	i : PLCR.2 CSTRO.T1 CSTRO.V1 o : PLCROUT (printer)	PLCR.J
UNPIN	UNPIN.S	UNPIN.X	i : UNPN.1A UNPN.3A UNPN.4A CSTRO.T1 o : UNPN.2A UNPNOUT (printer)	UNPN.J
INTSMF	INTSMF.S	INTSMF.X	i : INT.2 o : SMF.2 INTOUT (printer)	INT.J
ADSOIL	ADSOIL.S	ADSOIL.X	i : AD.2 SMF.2 o : ADOUT (printer)	AD.J
LUIN	LUIN.S	LUIN.X	i : LUIN.2 CSTRO.T1 o : LUINOUT (printer)	LUIN.J
TRIIN1	TRIIN1.S	TRIIN1.X	i : TRN.2 CSTRO.T1 o : TRNOUT (printer)	TRN.J
NETIN	NETIN.S	NETIN.X	i : NTN.2 CSTRO.N1 o : NTNOUT (printer)	NTN.J
SEGINS	SEGINS.S	SEGINS.X	i : SGN.2 CSTRO.N1 CSTRO.T1 o : SGNOUT (printer)	SGN.J

TABLE 5 (cont.)

PROGRAM	SOURCE	EXECUTABLE	DATA	JOBSTREAM
HECAD	HECAD.S	HECAD.X	i : CAL.1 RES.1 DIV.1 RAIN.1 HCD.1 SMF.2 CSTRO.N1 CSTRO.T1 o : HCD.2 HCDOUT (printer)	HCD.J
HEC-1		HEC1	i : HCD.2 header cards o : HEC1OUT (printer)	HEC1.J